COASTAL GROUNDWATER DISCHARGE AS A SOURCE OF NUTRIENTS TO HE'EIA FISHPOND, O'AHU, HAWAI'I

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ABSTRACT

Submarine groundwater discharge is volumetrically and chemically important to coastal zones and ecosystems. Ancient Hawaiians have known this for centuries, as Hawaiian fishponds were typically constructed not only around streams, but groundwater seepage and springs as well. To obtain a comprehensive understanding of coastal hydrology, processes, and ecosystems, is necessary to quantify SGD and SGD nutrient fluxes to coastal areas. In a Hawaiian fishpond setting, it is important to consider that SGD may be a significant source of nutrients. The chosen study site of this project was He‘eia Fishpond, a coastal pond on the north-east coast of O‘ahu in the state of Hawai‘i, into which He‘eia Stream flows. To identify sources of SGD in the pond, quantify SGD, and determine nutrient fluxes from SGD, we employed tracer techniques involving measurements of the isotopes ^{222}Rn, ^{223}Ra, and ^{224}Ra. Our results indicate the presence of fresh and brackish SGD, and suggest significant inputs of groundwater and groundwater-derived nutrients to He‘eia Fishpond. We found that the amount of water flux from SGD was about equal to that of He‘eia Stream. While fresh SGD was found to bring in about the same amount of nutrients as the stream, nutrient fluxes from brackish SGD greatly outweighed those of He‘eia Stream, suggesting that brackish SGD may be involved in the recycling of nutrients from higher trophic levels in He‘eia Fishpond. Our results show that the contribution of nutrients to fishpond ecosystems via SGD is just as important as stream inputs and deserves more attention from the scientific community.

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INTRODUCTION

Hawaiʻi, along with most island groups, relies heavily on its fresh and ocean water resources. Water has significant cultural, economic, and ecological significance. Sandy beaches, coral reefs, sea cliffs, and rich estuaries all provide a platform for life in Hawaiʻi. The ocean provides mankind with food, shoreline protection, marine recreation, aquaculture, and shipping pathways. Coral reefs are the biggest draw for tourists to Hawaiʻi. Hawaiian fishponds show how cultural and sustainable practices can revolve around stream and sea. Basically, water enables island existence, making it our most valuable resource. As such, there is a pressing need to evaluate and protect freshwater and ocean resources in the State of Hawaiʻi.

Threats to Water Sustainability and Ocean Health

The Hawaiian archipelago is facing a multitude of environmental issues due to over-population and climate change. Increase in population has led to pollution, increased demand for food and water, and over-development. As a consequence of increased food demand, over-fishing has become a major threat to biodiversity and fisheries stability. Development of coastal areas has caused loss of wetlands worldwide, and industrial activities have resulted in unprecedented increase in CO_2 emissions (Keeling et al. 1995). Considerable amounts of atmospheric CO_2 are absorbed by the oceans, leading to ocean acidification (Hoegh-Guldberg & Bruno 2010). Lowered ocean pH results in lessened ability of calcifying organisms to create calcium carbonate structures. The most dramatic effect of rising atmospheric CO_2 concentrations, though, is climate change.

Climate change is a global phenomenon, and its effects on Hawaiʻi have not gone unnoticed. Sea level rise has increased rates of shoreline erosion in Hawaiʻi, and may lead to coastal inundation, water drainage problems, and elevated property damage from large waves. Higher temperatures trigger increase in frequency and strength of heavy rainfall, floods, and tropical storms, while instigating a decrease in total rainfall overall. Hawaiʻi has already witnessed recent decreases in rainfall, reduction of stream flow, increased temperature, and sea level rise (Wallsgrove & Penn 2012). Data and models provide ample evidence that surface and subsurface freshwater resources are vulnerable and are likely to be strongly affected by climate change, with far-reaching societal and environmental consequences. Threats continue to build as time goes on, and steps need to be taken to minimize the impacts of further anthropogenic damage to the planet.

Concentrating on coastal problems in Hawaiʻi, we see that human activities have led to increased presence of invasive algae, loss of coral diversity, littoral eutrophication, coastal erosion, and reduced groundwater recharge rates. For example, watersheds neighboring Maunalua Bay, located on the south-east shore of Oʻahu, have been so altered by human activity in the past hundred years that coral reefs have dwindled (Wolanski et al. 2009). The whole ecosystem on the east side of the bay has collapsed, leading corals and coralline algae to their demise. Consequently, the bay has been subjected to decreased carbonate sediment production, the loss of an entire beach, and amplified wave breakage along the coast, resulting in shoreline erosion (Wolanski et al. 2009). Another example of negative human-induced change in Hawaiian marine environments is the proliferation of nonindigenous, invasive algae. The shift from coral to algal dominance in reef ecosystems has lead to loss of biodiversity, shifts in ecosystem food webs, and loss of habitat for reef fishes and other reef organisms (Smith et al. 2002). In urban and suburban areas with high population density, such as in south Kāneʻohe Bay, Oʻahu, eutrophication caused by increased, nutrient-rich runoff exacerbates the algae problem by triggering blooms that may have pushed reef communities beyond the point of recovery (Hunter & Evans 1995). Runoff can also cause aquifer depletion when it is diverted from its natural course into pipes and man-made channels, reducing groundwater recharge (Wolanski et al. 2009).

There is a need for cohesive action in order to facilitate adaptation to the inevitable environmental changes wrought by human activities. The vulnerability of the Hawaiian Islands cannot be combatted by relevant groups working separately, but instead by joining together. Increased water demand in Hawaiʻi has put immense pressure on water resource managers concerning water allocation and well-being (Kinzie et al. 2006). Managing vital water resources is only successful when partnerships exist between private and public sectors, government and public institutions, and so on. Local government, community groups, and even businesses can play a significant role in reshaping our future, while research provides a foundation for progress.

As human population explodes and global climate changes, it becomes important to explore interactions between the land and the ocean. Coastal zones are typically where these interactions occur, and are of commercial and economic importance. To build a sustainable, climate-conscious future, cohesive action is necessary. This includes consideration of SGD, or submarine groundwater discharge, when studying water and nutrient fluxes across the freshwater-saltwater interface. In Hawai‘i, understanding the processes that take place at the boundary of terrestrial and marine environments is crucial in preserving native ecosystems, culture, and way of life.

Riverine Systems

Streams and rivers are the primary pathway for freshwater traveling from land to sea, and are an important source of freshwater for human use. Currently, streams and rivers are in a precarious state, as annual water withdrawal rates increase. In addition, pollution, damming, and drought have led to unprecedented water level and water quality fluctuations in riverine systems, causing loss of habitat and biodiversity in riparian ecosystems worldwide (Oki & Kanae 2006).

Global Perspective

Globally, stream and river runoff is the most significant source of terrestrial sediments and new nutrients to the ocean. Depending on volume and flow, riverine energy can transport materials many miles off the coast into offshore waters. Runoff rates can change over very short time scales, whereas substantial changes in base flow occur at much longer time scales, since base flow is controlled by groundwater storage and recharge while runoff is controlled by rainfall and infiltration rates (Oki 2004).

In Hawai'i

Streamflow in Hawaii is variable over time and space. Between 1913-2002, stream base flow decreased in Hawaii. Rainfall also decreased during the same time period (Oki 2004) Streams that flow year-round in Hawai'i occur in areas that get a great deal of rainfall and groundwater discharge (Oki 2004), such as He'eia Stream in Kāne'ohe Bay. He'eia Stream had an average annual discharge of 1.1×10^6 m^3 for data collected between 2000 and 2013 by the USGS (Station #16275000). Maximum discharge in this area usually occurs in March and minimum discharge is typically seen in July. The stream is a major source of freshwater and nutrients to He'eia Fishpond (Briggs et al. 2013).

Submarine Groundwater Discharge

In addition to streamflow, submarine groundwater discharge (SGD) is an important pathway for nutrient and solute fluxes across the land-sea interface. This holds particularly true in Hawai'i. Studies have shown SGD to be a large contributor of freshwater and nutrients in O'ahu and across the state (e.g., Johnson et al. 2008, Kelly et al. 2013, Swarzenski et al. 2013).

Definition

The definition of groundwater and thus submarine groundwater discharge has been unclear in the past (Li et al. 1999). One definition of groundwater is water in the saturated zone of geologic material (Burnett et al. 2003). Another definition of groundwater is all subsurface water (Green et al. 2011).

Submarine groundwater discharge, or SGD, is defined as "any and all flow of water on continental margins from the seabed to the coastal ocean, regardless of fluid composition or driving force" (Burnett et al. 2003). Yet another explanation of SGD is "the exchange of fluid btw the coastal ocean and adjoining aquifers, where groundwater is a spatially and temporally variable mix of fresh meteoric groundwater and re-circulated seawater" (Street et al. 2008). Basically, SGD is the exchange of water from an underground aquifer to the coastal ocean. SGD is influenced by terrestrial and marine drivers such as tides, rainfall, waves, and sea level. Due to groundwater's enrichment in nutrients and other solutes in general, SGD has been shown to have significant effects on biogeochemical processes and hydrologic cycles in the coastal zone (Burnett et al. 2003).

Global Perspective

SGD is spatially and temporally variable, and usually consists of freshwater from an underground aquifer, recirculated seawater, or a mixture of both. It occurs in nearly every coastal area. SGD is driven by terrestrial and marine forces, including hydraulic gradients, tidal pumping, and current-induced pressure gradients (Burnett et al. 2003). Groundwater flows down-grade across a hydraulic gradient, meaning it flows directly into the ocean wherever a coastal aquifer is linked to the ocean (Burnett et al. 2001).

Estimates of fresh SGD vary significantly, generally ranging from 6-10% of total river discharge (Burnett et al. 2003), though it varies greatly depending on location. Moore et al.'s (2008) study suggests that SGD represents as much as 80-160% of river discharge in the North Atlantic. SGD is seasonally variable, being influenced by precipitation and evaporation (Kelly & Moran 2002). Generally, SGD decreases with increased depth and distance from a shoreline (Burnett et al. 2003).

Submarine groundwater discharge is volumetrically and chemically important to coastal zones (Burnett et al. 2001). Both fresh and salty groundwater reacts with sediments and buried organic matter, increasing levels of nutrients and trace metals in the water. Therefore, groundwater is biogeochemically significant in areas where it discharges (Burnett et al. 2003).

In Hawaiʻi

Groundwater is a major source of freshwater for public use, especially in Hawaiʻi (Burnett & Wada 2014). Groundwater provides approximately 99% of Hawaiʻi's domestic drinking water via artesian, or free-flowing, wells (Oki 2004). Owing to the permeability of lava rock and sedimentary deposits, Hawai‘i’s groundwater levels in the basal aquifer are close to sea level, allowing exchange between the basal lens and coastal zone to occur readily (Street et al. 2007).

Research has shown that SGD can significantly contribute to water and nutrient fluxes in coastal Hawaiian ecosystems (McGowan 2004, Johnson et al. 2008). In Kāne‘ohe Bay, fresh SGD was calculated to be twice that of previous estimates (McGowan 2004); as Kāne‘ohe Bay has already experienced problems with eutrophication-induced algae blooms, excess nutrients from SGD could exacerbate the problem. In Maunalua Bay, a strong linear relationship was found between terrestrial SGD and nutrient concentrations, indicating that fresh groundwater is a significant source of new nutrients to the bay (McGowan 2004). SGD in Honokohau Harbor, on the big island of Hawai’i, was also discovered in large amounts and was shown to convey nutrients to the littoral zone (Johnson et al. 2008). Land-use change and anthropogenic impacts may increase groundwater nutrient loads and lead to eutrophication; optimal nutrient inputs from groundwater discharge are essential for the balance of many coastal ecosystems.

Threats to Groundwater Systems

During the last half-century, direct and indirect consequences of human activities and climate change have led to groundwater depletion in large regions throughout the world. When rates of groundwater discharge are greater than rates of recharge, groundwater depletion occurs. Soil degradation, removal of native vegetation, increased demand for fresh water, and land use change are among the most prominent threats to groundwater reserves (Green et al. 2011). Decreased rainfall and streamflow in the past 100 years suggest an overall decline in groundwater levels, recharge rates, and SGD (Oki 2004). Shifts in groundwater discharge globally have even contributed to sea level rise in the past 100 years (Green et al. 2011).

Though most groundwater studies on the effects of climate change and population growth concentrate on reduced recharge and storage, groundwater quality is a pronounced issue that is likely to become more poignant in the future. Land use change and polluted runoff contribute to the degradation of underground aquifers, and suggest far-reaching implications, particularly in those societies that depend on groundwater for drinking (Green et al. 2011). Groundwater is a renewable yet slow-response resource, and must be prudently managed in the light of global change.

Hawaiian Fishponds

Man-made fishponds are distinctive features of Hawaiian coastlines that take advantage of terrestrial water and nutrient sources. Fishponds in Hawai'i date back 1500-1800 years (Costa-Pierce 1987) and cannot be found in such abundance or complexity in any other place in the Pacific (Kikuchi 1976). This ancient, integrated form of aquaculture required resource management, social organization, and a great deal of manpower (Costa-Pierce 1987). Although many Hawaiian fishponds today are in various states of decay, several attempts at restoration have been successful and have produced unique study sites for scientific investigation.

Hawaiian fishpond systems were similar to agriculture in that they both required strict management of water resources. Fishpond systems also mirrored agricultural practices in intensity of labor and time needed, not only to build but to maintain a functional practice. In terrestrial farming, the land must be tamed, fields or beds must be created, and maintenance is an everyday task; it was the same for fishponds. Just as plants had to be seeded, tended, and gathered, so fish had to be stocked, fed, and harvested (Kikuchi 1976).

Types of Hawaiian Fishponds

Four distinct types of Hawaiian fishponds were recognized (see Figure 1.1 on page 11; Kikuchi 1976). Loko iʻa kalo (freshwater taro fishponds) were agricultural ponds where kalo grew alongside fish that could withstand fresh and brackish water. Loko wai (freshwater fishponds) were ponds or lakes that were usually connected to the ocean, making them more fresh than salty, but still brackish. Loko puʻuone (brackish fishponds) were characterized as bodies of water geographically shut off from the sea, but permeable to seawater and incumbent salinity changes, somewhat resembling an estuary. Loko kuapā (seawater fishponds) were the most common of the ancient Hawaiian fishponds. In Hawaiian, loko means enclosed body of water, while kuapā means seawall (Kikuchi 1976, Costa-

Pierce 1987). The site of this study is He‘eia Fishpond, which is a loko kuapā fishpond (see Figure 1.2 on page 12).

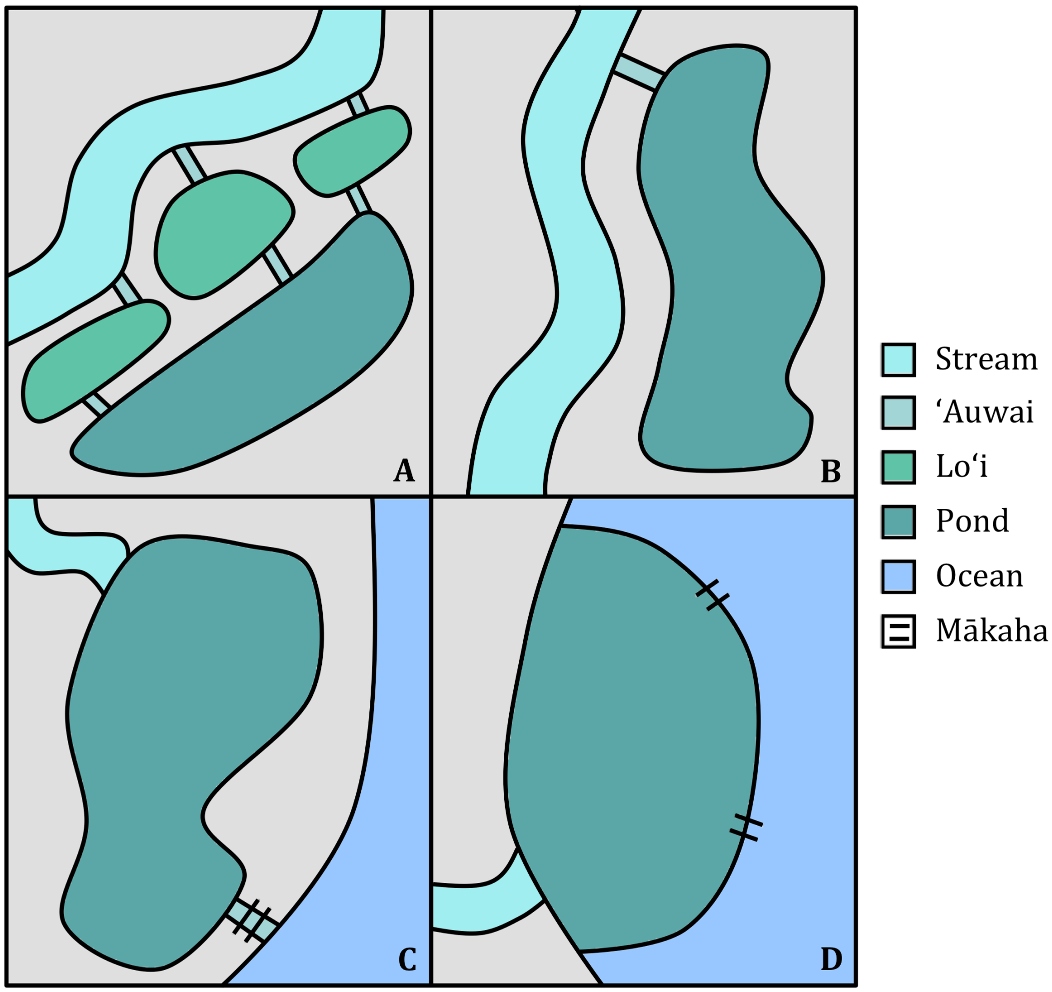


Figure 1.1 Types of Hawaiian Fishponds: A.) loko i‘a kalo, B.) loko wai, C.) loko pu‘uone, D.) loko kuapā

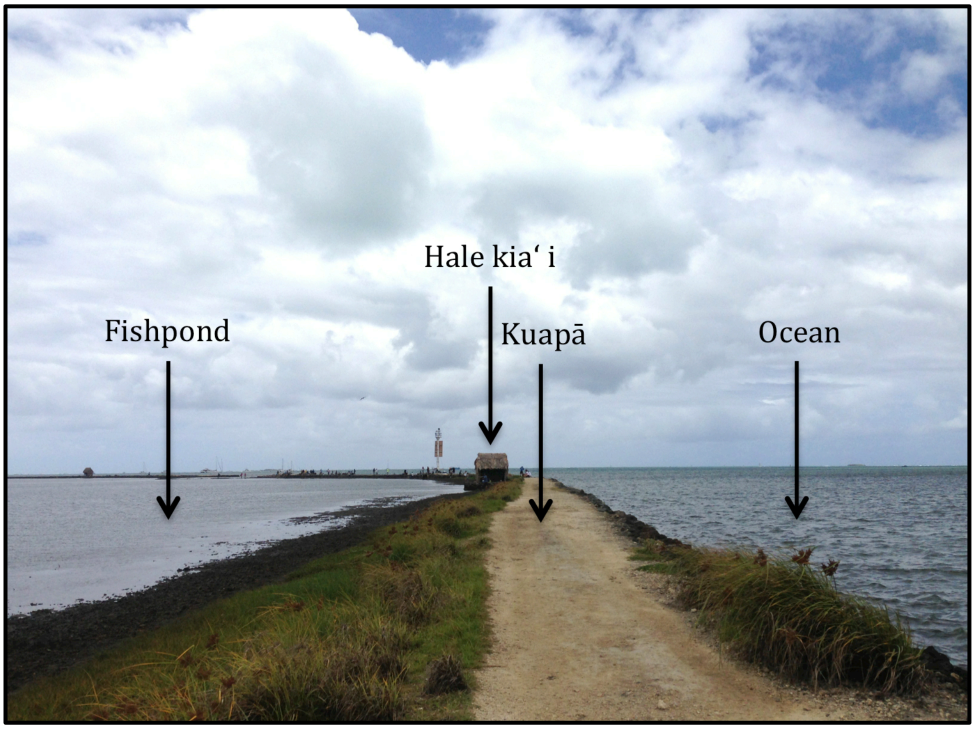


Figure 1.2 Hale kiaʻi and kuapā in Heʻeia Fishpond

Loko Kuapā Fishponds

Hawaiian loko kuapā fishponds, or simply loko kuapā, shared characteristics of other ancient Hawaiian fishponds, although they had some unique traits as well. Loko kuapā utilized the shoreline as a barrier and typically had a stream or spring bringing freshwater and nutrients into the pond. Seawalls of loko kuapā completed the pond barrier and were made of rock, coral, or a combination thereof. A seawall had small channels, called ʻauwai, leading to the ocean; the ʻauwai were controlled by sluice gates, or mākāhās, made from wood poles. The ʻauwai allowed seawater to circulate into the pond, carrying with it oxygen and nutrients. In addition, mākāhās were designed such that small fish could enter the fishpond freely, grow in a nutrient-rich, safe environment, and be unable to return to the ocean due to their increased size. Mākāhās also prevented the entry of large predatory fish to the pond. Loko kuapā were characterized by the presence of hale kiaʻi, or small hut-like shelters near the ʻauwai, in which the kiaʻi-loko, or caretaker of the pond, could rest during hot hours of the day (see Figures 1.3 & 1.4 on page 14; Kikuchi 1976). Fish commonly seen in loko kuapā fishponds were awa (milkfish), ʻamaʻama (mullet), palani and pualu (surgeonfish), papio (juvenile and small jackfish), kākū (barracuda), and ʻoʻopu hue (pufferfish). Other harvestable organisms included crabs, shrimp, eels, and limu (seaweed).

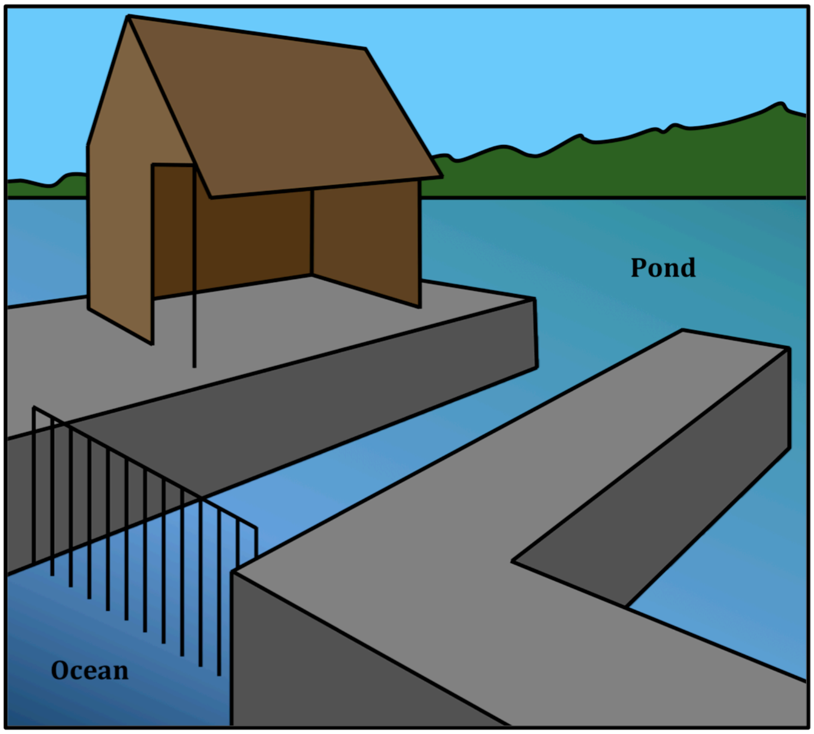


Figure 1.3 Front view illustration of loko kuapā with mākāhā, ʻauwai, and hale kiaʻi

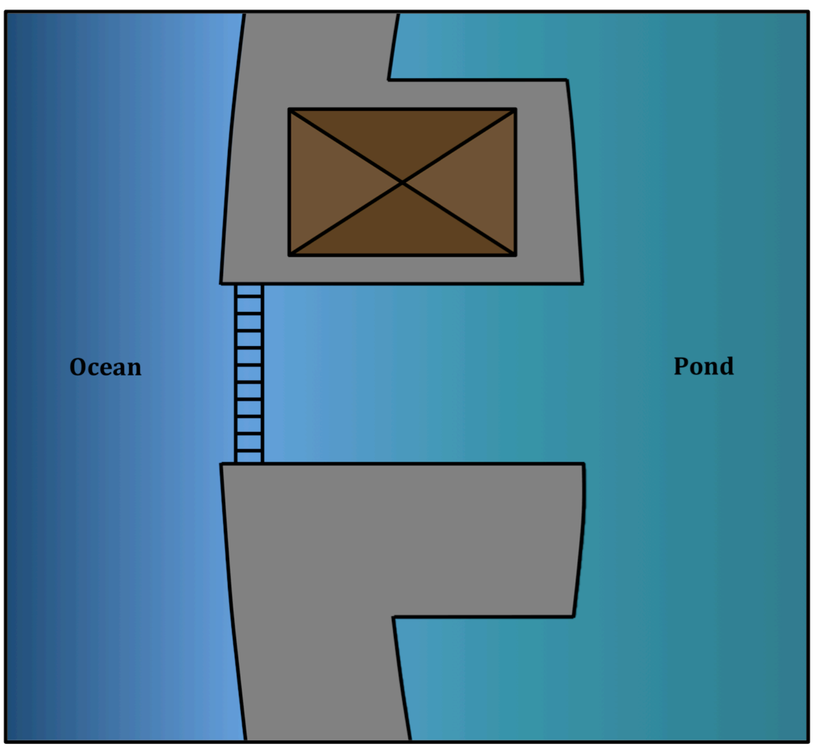


Figure 1.4 Top view illustration of loko kuapā with mākāhā, ʻauwai, and hale kiaʻi

Demise of Hawaiian Fishponds

The tradition of Hawaiian fishponds was changed forever following the discovery of Hawai‘i by Captain Cook in 1778. Preceding western influence, Hawaiian fishponds were controlled by ali‘i, or chiefs, who had sufficient authority to make the creation and maintenance of fishponds possible. After elimination of the kapu system in 1819, the introduction of capitalism established the idea of economic market efficiency (Kikuchi 1976). Due to fishponds' intensive labor needs and low yield, they became economically obsolete. No written record of Hawaiian fishpond management was created, and fishpond culture in Hawai‘i essentially diminished.

Most ancient Hawaiian fishponds are currently in various states of dilapidation from natural and anthropogenic causes. Wave action, floods, and tropical storms have led to the deterioration of fishpond structures, namely the seawalls. Human influence includes demolition of fishpond walls for recreation and development purposes (Kikuchi 1976). The introduction of mangroves to Hawaii in the early 1900s further exacerbated fishponds' demise. Although valued in other parts of the Pacific for shoreline protection, the invasive mangrove is regarded as a substantial ecological threat in Hawai'i. It is common to see mangroves disturb and overgrow native Hawaiian archaeological sites (Allen 1998). This holds particularly true in He‘eia Fishpond. Planted in He‘eia wetland in 1922 with the intention to capture sediment runoff and protect the coastline from sediments, mangroves flourished, making He‘eia home to the second-largest stand on

Oʻahu (Chimner 2006). Mangroves in Heʻeia ahupuaʻa have become the dominant shoreline vegetation and have wrought havoc on the seawall as well as indigenous plants (see Figure 1.5 below).

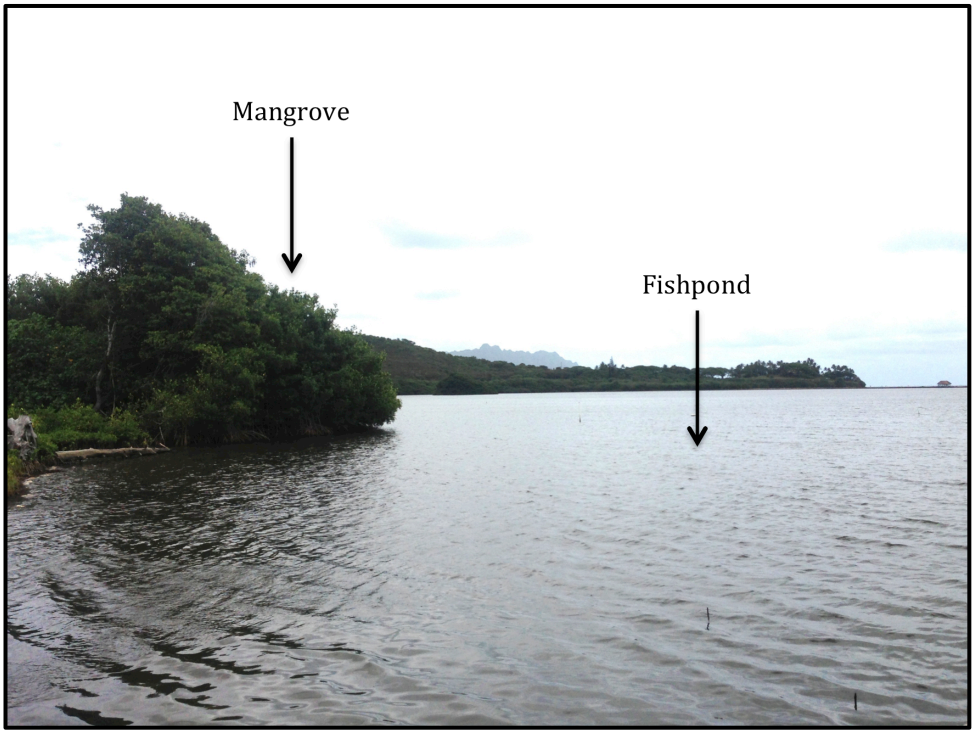


Figure 1.5 Invasive mangrove along the shoreline of Heʻeia Fishpond

<u>Heʻeia Ahupuaʻa</u>

Heʻeia Ahupuaʻa is located in Kāneʻohe Bay on the north-east shore of Oʻahu. It is comprised of Heʻeia Wetland, Heʻeia Fishpond, and several suburban neighborhoods. Heʻeia Ahupuaʻa has undergone a series of land use changes over the course of recent history, which makes it a unique and interesting study site.

History of Heʻeia Ahupuaʻa

Before the dissolution of Hawaiian hierarchy, Heʻeia Fishpond was one of the largest and most productive fishponds in the Hawaiian Islands. Until approximately 30 years ago, Heʻeia Pond was in a state of ruin, neglected by residents and encroached on by development (Paepae O Heʻeia). In recent years, however, interest in functionality and preservation of Hawaiian fishponds has become increasingly more common. At present, Heʻeia Fishpond is looked after by Paepae O Heʻeia, a private non-profit organization established in 2001.

The history of Heʻeia wetland mirrors that of Heʻeia Fishpond. Prior to contact with Western civilization, Hawaiians used Heʻeia wetland to farm kalo, or taro (see Figure 1.6 below). During the 1800s, however, kalo cultivation was replaced by sugarcane, pineapple, and rice production. Now most of the wetland is overrun with invasive California grass.

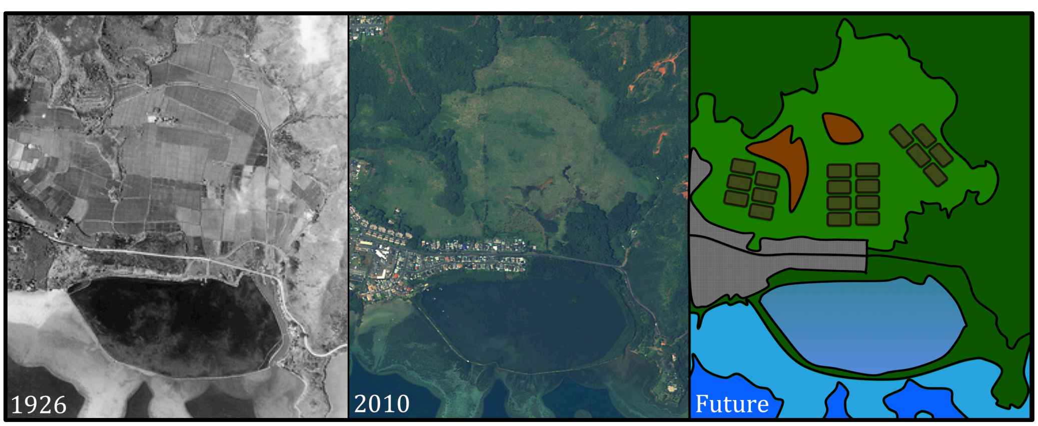


Figure 1.6 Past, current, and future land use change in Heʻeia ahupuaʻa. The future diagram depicts loʻis as small rectangles and recreation areas in brown. Photographs courtesy Honolulu Star Advertiser.

Restoration of He’eia Ahupuaʻa

Paepae O Heʻeia, the steward of Heʻeia Fishpond, organizes restoration efforts, which are largely volunteer-based. Current projects include the disposal of invasive mangrove, repair and reinstallation of the seawall, and community outreach programs to educate the public on the history and importance of ancient Hawaiian fishponds. Thus far, Paepae O Heʻeia has overseen the removal of over 75 meters of mangrove along the seawall (Karr & Buttner 2010).

To help preserve Heʻeia wetland, a local community organization by the name of Kākoʻo ʻŌiwi acquired a 38-year lease from the State of Hawaii in 2010 with the goal of returning the land to its original use of kalo farming. Other planned land use changes in Heʻeia wetland involve the construction of community recreation areas, a poi mill, a health center, and possibly even a farmer’s market. With the reintroduction of intensive, traditional Hawaiian kalo cultivation, it is necessary to assess possible changes in nutrient and sediment fluxes to the fishpond downstream, which will inevitably receive a differed amount of particulate matter and nutrients as a result.

Study Site

Heʻeia Fishpond is a coastal pond located in Kāneʻohe Bay on the north-east shore of Oʻahu (see Figure 1.7 on page 20). The pond supports a shallow, low-energy ecosystem. It is bordered by mangrove forest along the coastline and by coral on the

Kāneʻohe Bay side. Heʻeia Fishpond receives freshwater and nutrients from terrestrial runoff and SGD, and seawater from Kāneʻohe Bay (Briggs et al. 2013).

Heʻeia Fishpond was built 600-800 years ago and took approximately 2-3 years to complete (Paepae O Heʻeia). The pond encompasses an area of about .15 square miles and is partially bounded by a seawall around 2.1 km (1.3 mi) in length (Karr & Buttner 2010). The seawall is 4-5 m wide and is made up of volcanic rock filled in with coral, making it semi-permeable. Three mākāhās, or sluice gates, are located where Heʻeia Stream enters the pond, and another three mākāhās are located along the seawall (Paepae O Heʻeia).

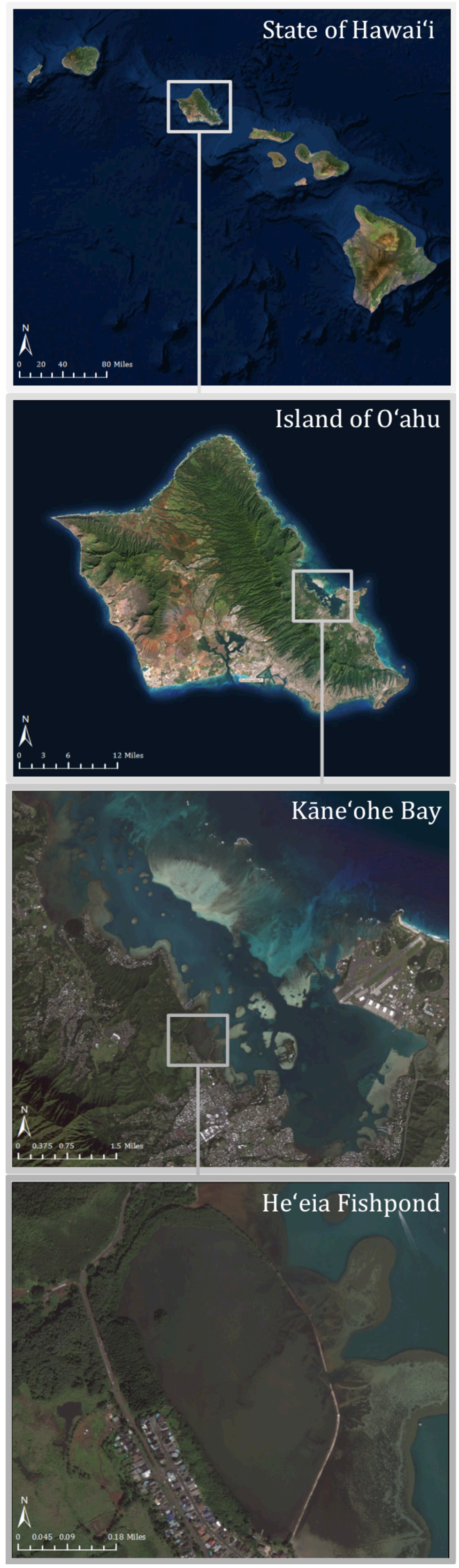


Figure 1.7 Location of Heʻeia Fishpond

Research Goals

Terrestrial inputs from streams and groundwater are important components of the water and nutrient cycles of Hawaiian Fishponds, yet little is known about groundwater-derived nutrients. Of particular importance is the comparison of SGD vs. stream inputs of water and nutrients to the fishpond setting in He‘eia Ahupua‘a, since land use change is occurring in the wetland directly upstream. It is imperative to further our understanding of baseline water and nutrient fluxes now in order to evaluate changes that may occur in the future due to climate and land use change.

Hypothesis

Submarine groundwater discharge is a significant source of new nutrients to He‘eia Fishpond.

Objectives

Our objectives for this project are to 1.) determine locations of groundwater discharge and identify groundwater sources to He‘eia Fishpond, 2.) quantify and compare SGD and He‘eia Stream inputs to the pond, and 3.) quantify and compare nutrient fluxes from SGD and He‘eia Stream to the pond.

The broader impacts of this project link together scientific and community efforts to better understand He‘eia Fishpond’s ecosystem, which is driven by nutrient availability (see Figure 1.8 on page 23). Nutrients are the basis of the pond’s food web and support the growth of autotrophs that are an essential food source for fish in the pond. The most significant source of nutrients to He‘eia Fishpond may in fact be SGD.

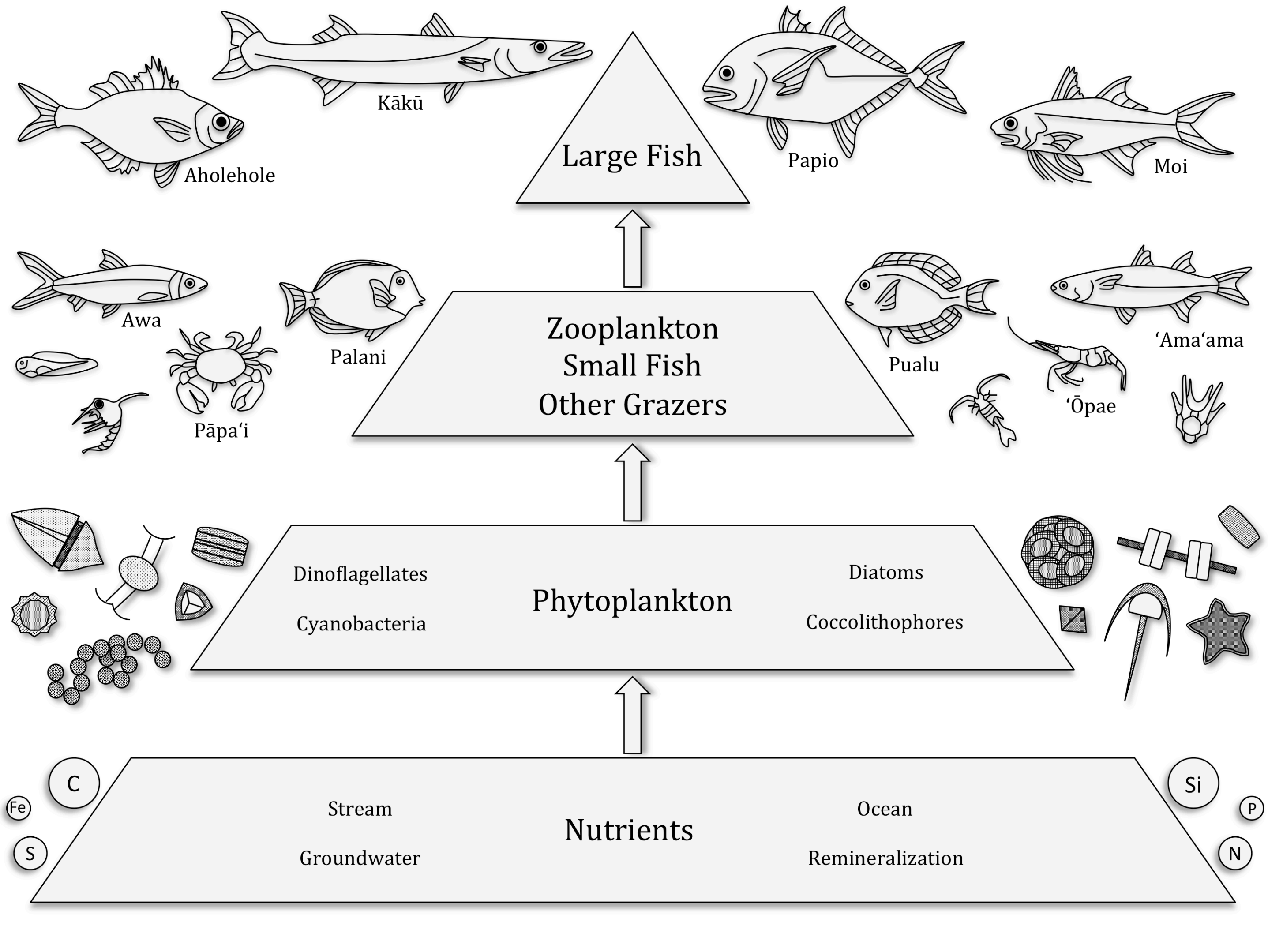


Figure 1.8 Conceptual diagram of Heʻeia Fishpond ecosystem

METHODS

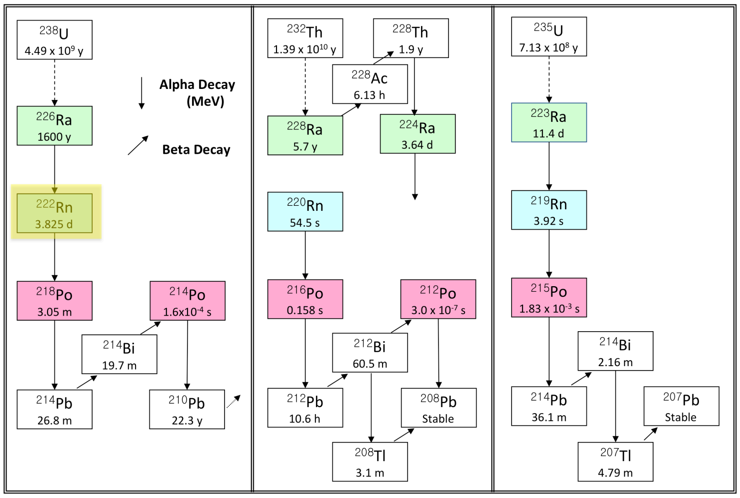
While riverine inputs and their effects on coastal ecosystems are obvious and well understood, the flux and influence of groundwater discharge to coastal zones remain elusive, as direct groundwater discharge is inherently very difficult to measure (Burnett et al. 2001). Three basic approaches to evaluation of SGD are modeling, direct measurement, and chemical tracers. In this study, we utilized the latter tracer technique to identify sources of groundwater and quantify SGD using ^{222}Rn, ^{223}Ra, and ^{224}Ra. We also measured salinity at various locations to better explore sources of SGD. To examine nutrients in He‘eia Fishpond, we collected water samples and utilized nutrient concentrations from other studies in calculation of nutrient fluxes from SGD and He‘eia Stream.

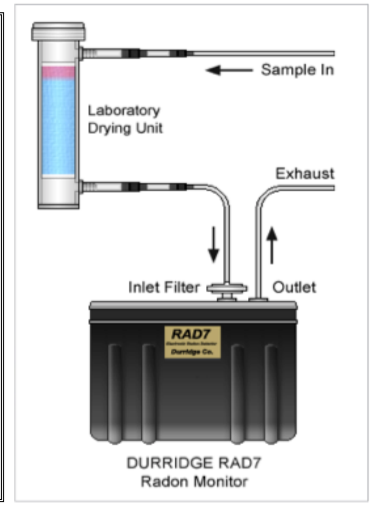
Identifying Groundwater Sources

Our approach to identifying groundwater sources involved the isotope ^{222}Rn along with measurements of surface salinity. Radon-222 was used as a proxy for SGD, while salinity distinguished different sources of groundwater. Combining radon and salinity data allowed us to classify and characterize groundwater inputs to He‘eia Fishpond.

Radon: Groundwater Presence

To reveal areas of He‘eia Fishpond where submarine groundwater discharge occurs, we surveyed the pond’s surface water for ^{222}Rn. Radon-222 is elevated in both fresh and salty groundwater from contact with uranium-bearing minerals in the aquifer and can therefore be used as proxy for SGD (Burnett & Dulaiova 2003). Radon-222 has a half-life of 3.8 days (see Figure 2.1 on page 26), and is a noble gas that is prone to evasion to the atmosphere, thus it was necessary to measure its activity levels directly in the field. We used a RAD7 electronic radon detector, made by Durridge Company (see Figure 2.2 on page 26) outfitted with a RAD-Aqua system to convert radon in water to radon in air (Dulaiova et al. 2005). The pump water intake was positioned about 0.15 m below the water surface to capture any buoyant groundwater plumes. During a continuous radon survey, a total of 16 measurements were taken in five-minute integrated intervals between 13:15-14:30 on 11/19/14. We surveyed the pond during low tide with the intent that the radon signature to be least diluted by flood tide from Kāneʻohe Bay, which is low in radon. For this reason, reported ^{222}Rn results are biased toward higher groundwater contributions to Heʻeia Fishpond.





Figures 2.1 & 2.2 Radon-222 decay chain; RAD7 device

Salinity: Groundwater Sources

To further investigate sources of SGD to He‘eia Fishpond, we measured salinity using four different methods. To address spatial and temporal distribution of salinity in the pond from stream and groundwater inputs, we employed in situ salinity measurement devices (YSI 6920 V2-2 sonde, Schlumberger CTD-Diver) and collected water samples for laboratory analysis. For temporal monitoring we placed CTD divers at three different locations in He‘eia Fishpond pond over one tidal cycle. In addition, surface and bottom salinities were manually measured at seven locations in the pond using a hand-held YSI V2-2 sonde equipped with a salinity probe, which was calibrated prior to deployment using YSI conductivity standards. Nutrient and grab water samples were collected and examined to evaluate spatial salinity distribution. Salinity from nutrient samples was analyzed at the SOEST Laboratory for Analytical Biogeochemistry (S-LAB) in 2 runs using a

Metrohm 856 Conductivity Module, from which average salinity was calculated. Salinity from grab samples was determined in laboratory setting using the same YSI V2-2 hand-held device that was operated in the field. Reported accuracies of the individual techniques were as follows: YSI V2-2 sonde has an accuracy of 1% or 0.1; CTD diver has an accuracy of 1%; S-Lab titration has an accuracy of 1.6%.

Quantifying SGD

The approach we took to quantify submarine groundwater in He'eia Fishpond required three parameters. The first was radon inventories for the pond, which we acquired during the spatial surface water radon survey. Second, radon groundwater concentrations had to be known, which were measured during a separate portion of this project in He'eia Wetland (Dulaiova 2013). Last, we needed water residence times, because radon mass balance in water is based upon how much radon must enter the pond via SGD to replace what is removed by mixing (Charette et al. 2008). Using a geochemical approach involving isotopes ^{224}Ra and ^{223}Ra, we were able to calculate apparent radium age as an estimate for water parcel age in the pond. Once water ages were determined, we calculated SGD in He'eia Fishpond.

SGD Calculations

To calculate groundwater flux to He'eia Fishpond, we employed the approach described in Charette et al. (2008), using the equation:

$$F_{SGD} = \frac{\left(\left[\frac{(A-A_{ocn})}{T_w}\right]-[Diffusion]+[Evasion]+[Decay]\right)}{A_{gw}} \quad (1)$$

where F_{SGD} is fluid flux via SGD, A is average activity of ^{222}Rn in the study area, A_{ocn} is the activity of ^{222}Rn in Kāneʻohe Bay, T_w is water residence time in the pond, and A_{gw} is ^{222}Rn activity in groundwater. Diffusion is the enrichment of radon in water due to release of pore water from sediments (bioturbation, erosion, molecular diffusion), which is not considered SGD. Evasion is the loss of radon as a result of its escape to the atmosphere from surface waters; evasion values tend to be significant. Decay is the loss of radon in water from its decay to daughter isotopes.

We calculated A during our ^{222}Rn survey in Heʻeia Fishpond, A_{ocn} was assumed to be equal to Kāneʻohe Bay dissolved ^{226}Ra, the parent isotope of ^{222}Rn (Dulaiova 2013), and A_{gw} was measured previously (Dulaiova 2013). Diffusion, evasion, and decay calculations were executed based on the procedures outlined in Charette et al. 2008. The remaining parameter to calculate SGD was water residence time, T_w,, which we obtained via analysis of radium isotopes ^{223}Ra and ^{224}Ra.

Radium: Water Residence Time

The short-lived radium isotopes ^{223}Ra ($t_{1/2}$=11.3d) and ^{224}Ra ($t_{1/2}$=3.7d) are continuously regenerated in groundwater from thorium decay (see Figure 2.3 on page 31; Street et al. 2008). Radium isotopes are disconnected from their respective parents and start to decay once groundwater discharges into He‘eia Fishpond. As a radium-enriched water parcel ages, the ratio ^{224}Ra:^{223}Ra decreases since ^{224}Ra decays much faster than ^{223}Ra. Using equation 2 from Moore (2000), we were able to calculate apparent radium ages of water parcels in He‘eia Fishpond as a proxy for water parcel residence time in our SGD calculations.

To collect radium isotopes ^{223}Ra and ^{224}Ra, manganese oxide-coated fibers were placed at selected locations in He‘eia Fishpond, as well as one in He‘eia Stream. From the water, ^{223}Ra and ^{224}Ra adsorb onto manganese oxide-coated fibers quantitatively. Five Mn fibers were inundated with water from grab samples to represent snap-shot radium values in the pond at low tide. An additional twelve Mn fibers were placed at different locations in He‘eia Fishpond as passive collectors deployed over a full tidal cycle, for a total 17 fibers. The grab samples were collected to determine absolute radium isotope activities, and only represent a snapshot of activity at one time. While the tidal fibers give an integrated radium sample, they only provide accurate radium activity ratios, as the water volume they encounter during deployment is unknown.

The semi-dry fibers were assessed in a radium delayed coincidence counter, or RaDeCC (see Figure 2.4 on page 31), immediately, at 1 month, and again at 3 months. The RaDeCC counts alpha particles from Rn decay, which are then corrected for chance coincidences and decay since time of sample collection (Moore & Arnold 1996). To account for ^{228}Th-supported ^{224}Ra activity, the ^{224}Ra 1-month count was subtracted from the ^{224}Ra 1-week count.

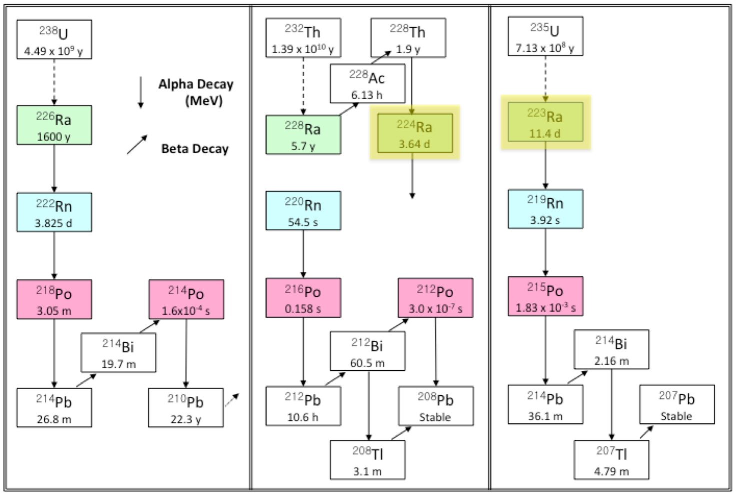
Apparent radium ages were determined using the activity ratio ^{224}Ra:^{223}Ra by means of the equation described by Moore (2000):

$$\left[\frac{224\mathrm{Ra}}{223\mathrm{Ra}}\right]_{\mathrm{obs}} = \left[\frac{224\mathrm{Ra}}{223\mathrm{Ra}}\right]_{\mathrm{i}} \frac{\mathrm{e}^{-\lambda_{224}\mathrm{t}}}{\mathrm{e}^{-\lambda_{223}\mathrm{t}}} \qquad (2)$$

and its simplified form:

$$T = \frac{\ln{(AR_{gw})} - \ln{(AR_{pond})}}{\lambda_S - \lambda_L} \qquad (3)$$

where initial ^{224}Ra/^{223}Ra is assumed constant. Uncertainties of all radium measurements were calculated by error propagation based on counting statistics (Garcia-Solsona et al. 2010). Uncertainties of water ages were calculated by error propagation (Knee et al. 2011).



Figures 2.3 & 2.4 Radium-223 & Radium-224 decay chain; radium delayed coincidence counter

<u>Evaluating Nutrient Fluxes</u>

Nutrient concentrations in groundwater tend to be high in comparison to seawater. For this reason, even small amounts of SGD can be influential to coastal ecosystem nutrient levels (Li et al. 1999). With the upsurge of coastal development in the Hawaiian Islands, there is a pressing necessity to research current nutrient budgets (Street et al. 2008).

Nutrient Concentrations

To address spatial distribution of nutrients in He‘eia Fishpond, we took water samples at 9 sites in He‘eia Fishpond. The samples were filtered, bottled, kept in dark at low temperature, and subsequently evaluated at the SOEST S-LAB. Total N, total P, phosphate reported as dissolved inorganic phosphorous (DIP), silicate, and NO_3^- + NO_2^- and ammonia reported as dissolved inorganic nitrogen (DIN) were measured using an AA3 Nutrient Autoanalyzer, utilizing methods and procedures outlined by the manufacturer Seal Analytical (soest.hawaii.edu/S-LAB).

Nutrient Fluxes

To determine nutrient fluxes in He‘eia Fishpond, we multiplied our SGD fluxes by known nutrient concentrations from other publications (see equation 4). To calculate fresh SGD nutrient fluxes, we used He‘eia Wetland nutrient concentrations from Dulaiova (2013). To calculate brackish SGD nutrient fluxes, we used He‘eia Fishpond pore water nutrient concentrations from Briggs et al. (2013). To determine nutrient fluxes from He‘eia Stream, we used USGS discharge data from Haiku Station (#16275000), of which 50% is estimated to reach He‘eia Fishpond (Young 2011), as well as He‘eia Stream nutrient concentrations from Hoover & Mackenzie (2009).

$$Nutrient\ Flux = Discharge \times Nutrient\ Concentration \tag{4}$$

RESULTS

Groundwater Sources

Several SGD sources were identified in He‘eia Fishpond using radon and salinity measurements. ^{222}Rn data indicated three main areas, or plumes, of SGD in the pond. Salinity measurements allowed us to classify SGD as fresh or brackish.

Radon: Spatial Variability

Radon-222 was measured in the surface water of He‘eia Fishpond using a RAD-Aqua instrument, described earlier (see Table 3.1 on page 34). Readings were targeted to map the radon distribution of the pond at low tide when radon signature would be least diluted by flood tide. Minimum radon in water was 0.9 dpm/L measured in the northern portion of the pond, which we estimated to be the baseline radon value in the pond supported by diffusion from sediments. Maximum radon in water was 2.8 dpm/L and was observed in the southern center of the pond. Average radon in water was 1.9 dpm/L with a standard deviation of 0.6 dpm/L. There were several locations of elevated radon signature across He‘eia Fishpond that suggest the presence of groundwater discharge. From Figure 3.1 on page 35, where larger radon values indicate groundwater presence, we can visualize three plumes of SGD: 1.) where He‘eia Stream discharges, 2.) on the south-west shoreline, and 3.) along the seawall.

Table 3.1 Radon-222 Concentrations in He‘eia Fishpond on 11/19/13

Time	Latitude (N)	Longitude (W)	Rn222 (dpm/L)
13:15	21.43203	157.80703	1.1 ± 1.3
13:20	21.43353	157.80821	2.6 ± 1.7
13:25	21.43467	157.80893	1.8 ± 1.6
13:30	21.43595	157.80984	1.1 ± 1.3
13:35	21.43741	157.81051	2.7 ± 2.0
13:40	21.43885	157.81027	2.0 ± 1.7
13:45	21.43898	157.80933	1.1 ± 1.3
13:50	21.43751	157.80875	1.6 ± 1.4
13:55	21.43608	157.80821	2.0 ± 1.6
14:00	21.43466	157.80765	2.8 ± 1.9
14:05	21.43336	157.80682	1.6 ± 1.4
14:10	21.43356	157.80577	1.5 ± 1.4
14:15	21.43505	157.80531	2.2 ± 1.7
14:20	21.43708	157.80586	2.2 ± 1.7
14:25	21.43882	157.80728	2.0 ± 1.5
14:30	21.43949	157.80909	0.9 ± 1.3

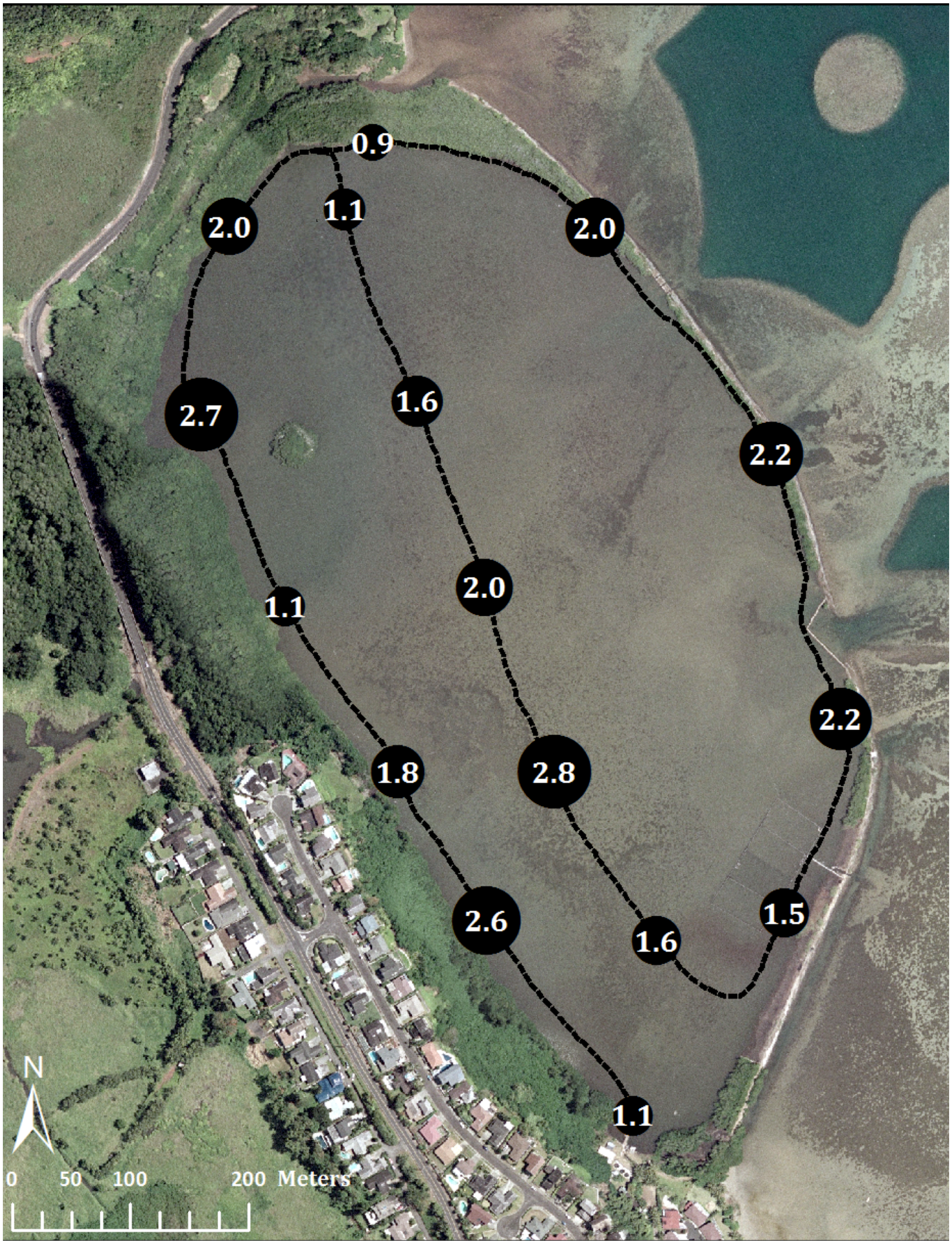


Figure 3.1 Radon-222 concentrations (dpm/L) in He‘eia Fishpond on 11/19/13

Salinity: Spatial & Temporal Variability

Surface and bottom salinities were measured manually using a handheld YSI at seven locations in He‘eia Fishpond (see Table 3.2 on page 38 & Figure 3.2 on page 39). These measurements were taken during rising tide, when water level was approximately +0.2 meters above mean water level. Salinity from 9 discrete samples was measured in two runs, from which the average was used. Surface salinity was also measured from grab samples collected at four different locations in He‘eia Fishpond.

The lowest recorded surface salinity was 11.5 near He‘eia Stream. The highest recorded surface salinity was 33.5 adjacent to the seawall. Average surface salinity was 28.7 with a standard deviation of 7.0. The average bottom salinity was 32.8 with a standard deviation of 0.5. Surface salinity was seen to vary much more than bottom salinity, which was expected as dense salt water sinks to the bottom of the pond and is less variable than the dynamic, stratified surface estuarine layer.

Divers were placed at three different locations in He‘eia Fishpond to record salinity over 1 tidal cycle (see Figure 3.2 on page 39). Minimum salinity recorded at Station 7 was 25.8 recorded at 13:40 on 11/19/13, which was +0.5 m relative to MLLW (water level from NOAA Moku o Lo‘e station #1612480 in Kāne‘ohe Bay). Maximum salinity was 33.4 recorded at 9:10 on 11/20/13, which was -0.1 m relative to MLLW. Average salinity at Station 7 was 32.0 with a standard deviation of 1.3. Minimum salinity recorded at Station 3 was 16.1 recorded at 19:10 on 11/19/13, which was

+0.1 m relative to MLLW. Maximum salinity was 34.7 recorded at 3:15 on 11/20/13, which was -0.1 m relative to MLLW. Average salinity at Station 3 was 28.9 with a standard deviation of 4.1. Minimum salinity recorded at Station 16 was 28.8 at 14:40 on 11/19/13, which was at +0.4 m relative to MLLW. Maximum salinity was 32.8 recorded at 1:30 on 11/20/13, which was +0.1 m relative to MLLW. Average salinity at Station 16 was 32.3 with a standard deviation of 0.7. Station 3 saw the largest standard deviation and lowest observed salinity indicating the largest freshwater and tidal influence.

Table 3.2 Salinity in He'eia Fishpond on 11/19/13

Station ID	Latitude (N)	Longitude (W)	Time	*Surface Salinity	*Bottom Salinity
HeeiaFP_1	21.43457	157.80553	11:46	33.5	33.5
HeeiaFP_3	21.43667	157.80594	11:42	33.3	33.3
HeeiaFP_7	21.43919	157.80954	11:13	31.0	32.7
HeeiaFP_8	21.43801	157.80899	11:24	31.9	32.1
HeeiaFP_9	21.43677	157.80840	11:31	32.0	32.6
HeeiaFP_11	21.43477	157.80696	11:49	32.3	32.3
HeeiaFP_19	21.43803	157.81009	11:10	23.0	33.0

Station ID	Latitude (N)	Longitude (W)	Time	*Grab Sample Salinity
HeeiaFP_G8	21.43801	157.80899	11:24	31.4-31.9
HeeiaFP_G9	21.43677	157.80840	11:31	32.0
HeeiaFP_G18	21.43711	157.81024	10:54	13.6
HeeiaFP_Gdock	21.43198	157.80710	11:57	31.4

Sample ID	Latitude (N)	Longitude (W)	Time	Average Salinity
HeeiaFP_N1	21.43475	157.80899	13:25	30.0
HeeiaFP_N2	21.43731	157.81049	13:35	11.5
HeeiaFP_N3	21.43942	157.80945	13:44	20.6
HeeiaFP_N4	21.43721	157.80844	13:52	32.6
HeeiaFP_N5	21.43451	157.80760	14:01	32.2
HeeiaFP_N6	21.43297	157.80606	14:09	33.1
HeeiaFP_N7	21.43470	157.80525	14:14	33.4
HeeiaFP_N8	21.43782	157.80643	14:23	32.9
HeeiaFP_N9	21.43935	157.80821	14:27	32.4

*Salinity error is 1% as reported by YSI 6920 V2-2 sonde salinity probe accuracy

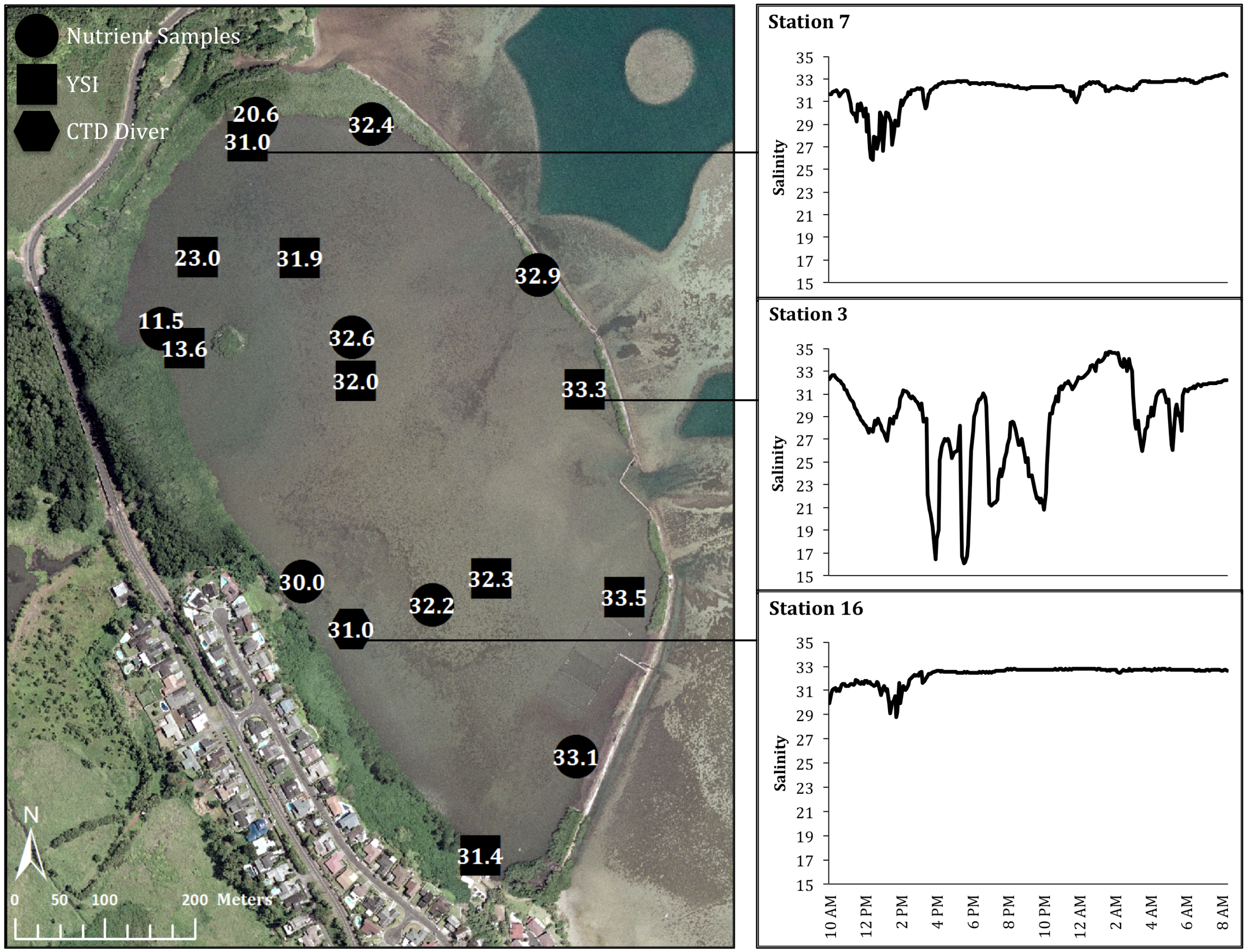


Figure 3.2 Salinity in He'eia Fishpond on 11/19-20/13. Note two diver symbols not present due to overlap with salinity measurements taken via YSI.

Submarine Groundwater Discharge

Radium: Spatial Variability

Absolute activities of ^{223}Ra from grab samples ranged from 2-8 dpm/m^3 (see Table 3.3 on page 42), with an average of 5 dpm/m^3 and standard deviation of 2 dpm/m^3. Absolute activities of ^{224}Ra from grab samples ranged from 13-39 dpm/m^3 with an average of 26 dpm/m^3 with a standard deviation of 10 dpm/m^3.

Radium-224:radium-223 activity ratios from grab samples ranged from 4.1 to 7.9 (see Figure 3.3 on page 43), matching tidal samples fairly closely. Average ^{224}Ra: ^{223}Ra from these samples was 5.7 with a standard deviation of 1.6. ^{224}Ra: ^{223}Ra activity ratios from fibers left in the pond and stream over one tidal cycle ranged from 0.3 in He'eia Stream to 7.0 at the north-east pond border (see Figure 3.4 on page 44). Average ^{224}Ra: ^{223}Ra activity ratios from fibers left in the pond over one tidal cycle was 4.1 with a standard deviation of 1.7.

Our radium analysis suggests that He'eia stream is not a significant source of radium and it is probably outcompeted by SGD inputs. The radium activity ratios indicate that water parcels near He'eia Stream have low residence times, while other areas of the pond, most notably the southern region, seem to have longer water parcel residence times and experience slow recirculation (see Figure 3.5 on page 45). Water parcels near He'eia Stream likely have low residence times due effective flushing caused by streamflow and the connection to the ocean through the mākāhā. However, SGD could play a part in flushing water out of this area as well, as we see high radon values. Low residence times revealed in the south portion of the pond are not surprising, as there is little wave energy and few currents within that section of the pond.

Groundwater Fluxes

Using our radon inventories, groundwater radon concentrations from the wetland, and estimated water age, we were able to approximate SGD fluxes to He‘eia Fishpond. Our calculations show large contributions of groundwater to the pond. Localized measurements of SGD are in m^3/day per meter of shoreline (see Table 3.4 on page 46). Results indicate that fresh groundwater discharges at 317 cubic meters of water per day, brackish groundwater discharges at 2209 m^3/day, and total SGD amounts to 2525 m^3/day. From USGS data for 11/18-20/13, He‘eia Stream was shown to discharge at 2139 m^3/day. Our SGD calculations suggest that during baseline conditions, fresh groundwater discharges at about 14.8% of stream discharge, brackish groundwater discharges at 103% of stream discharge, and total groundwater discharges at 118% of stream discharge.

Table 3.3 Radium Concentrations in He‘eia Fishpond on 11/19-20/13

Station ID	Latitude (N)	Longitude (W)	Time In (11/19/13)	Time Out (11/20/13)	*Ra224 dpm/sample	*Ra223 dpm/sample	Ra224:Ra223
HeeiaFP_1	21.43457	157.80553	11:46	9:44	2375 ± 150	623 ± 66	3.80 ± 0.47
HeeiaFP_3	21.43667	157.80594	11:42	9:40	2447 ± 198	623 ± 76	3.93 ± 0.64
HeeiaFP_6	21.43906	157.80809	11:21	9:33	1641 ± 48	234 ± 38	7.01 ± 1.67
HeeiaFP_7	21.43919	157.80954	11:13	9:27	1708 ± 87	321 ± 57	5.32 ± 0.87
HeeiaFP_8	21.43801	157.80899	11:24	9:30	1317 ± 47	403 ± 29	3.27 ± 0.53
HeeiaFP_9	21.43677	157.80840	11:31	9:37	1969 ± 75	422 ± 36	4.67 ± 0.76
HeeiaFP_11	21.43477	157.80696	11:49	9:46	2666 ± 175	634 ± 91	4.21 ± 0.59
HeeiaFP_14	21.43258	157.80742	10:44	9:15	558 ± 126	198 ± 53	2.82 ± 0.60
HeeiaFP_16	21.43427	157.80847	10:50	9:18	1242 ± 151	350 ± 44	3.55 ± 0.63
HeeiaFP_18	21.43711	157.81024	10:54	9:23	339 ± 103	82 ± 57	4.13 ± 1.57
HeeiaFP_19	21.43803	157.81009	11:10	9:26	864 ± 149	148 ± 61	5.84 ± 1.50
HeeiaFP_stream	21.43562	157.81105	15:13	9:00	4 ± 5	12 ± 6	0.31 ± 0.47

Station ID	Latitude (N)	Longitude (W)	Sampling Time (11/19/13)	**Ra224 dpm/m^3	**Ra223 dpm/m^3	Ra224:Ra223
HeeiaFP_G7	21.43919	157.80954	11:13	23 ± 0.8	5 ± 0.4	4.67 ± 1.00
HeeiaFP_G8	21.43801	157.80899	11:24	20 ± 1.6	4 ± 1.0	4.98 ± 1.17
HeeiaFP_G9	21.43677	157.80840	11:31	39 ± 1.5	6 ± 0.9	6.54 ± 3.24
HeeiaFP_G18	21.43711	157.81024	10:54	13 ± 2.5	2 ± 3.0	7.93 ± 1.91
HeeiaFP_Gdock	21.43198	157.80710	11:57	33 ± 1.7	8 ± 0.9	4.14 ± 0.52

*Ra error based on counting statistics

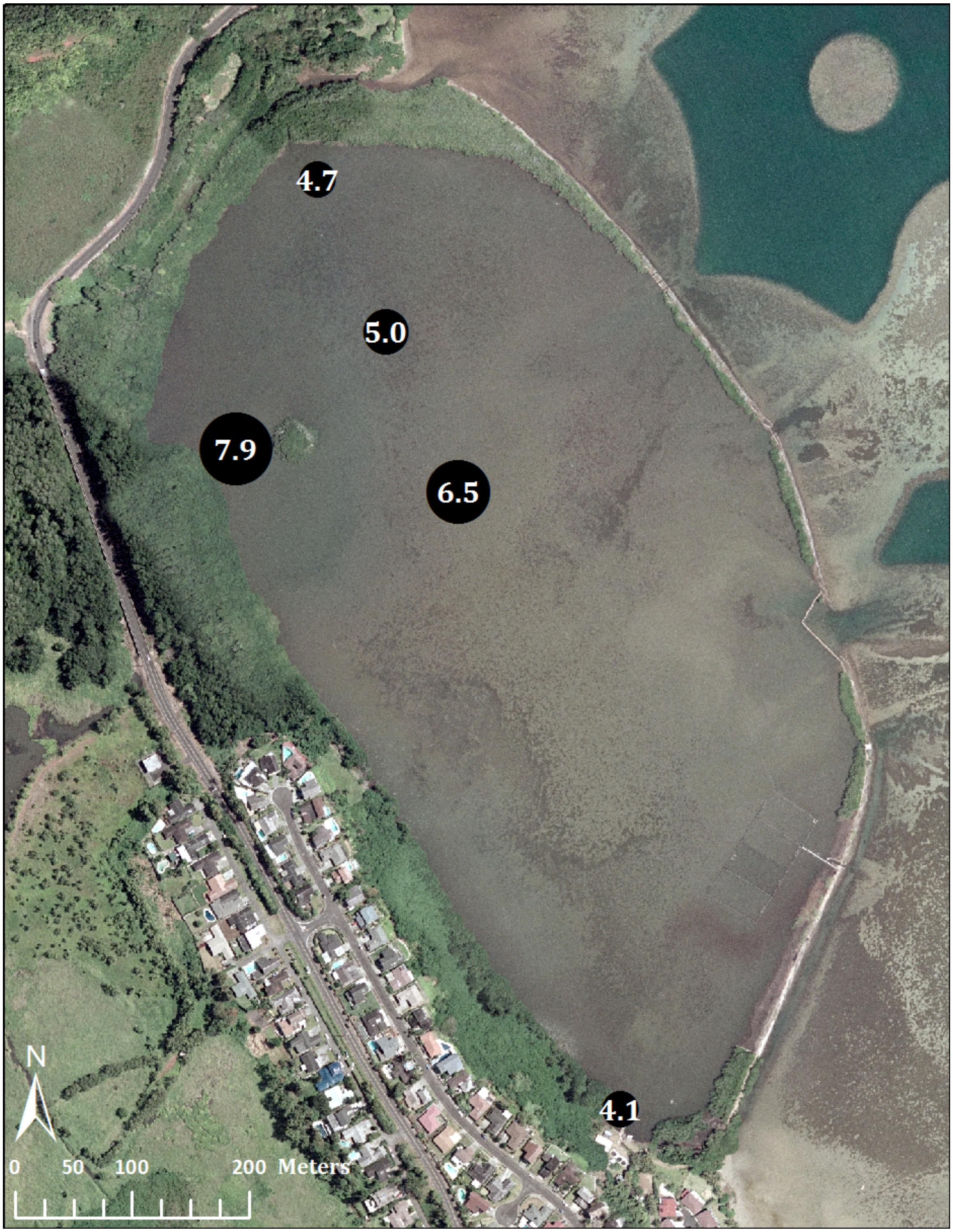


Figure 3.3 Radium-224:radium-223 activity ratios from grab samples in Heʻeia Fishpond on 11/19-20/13

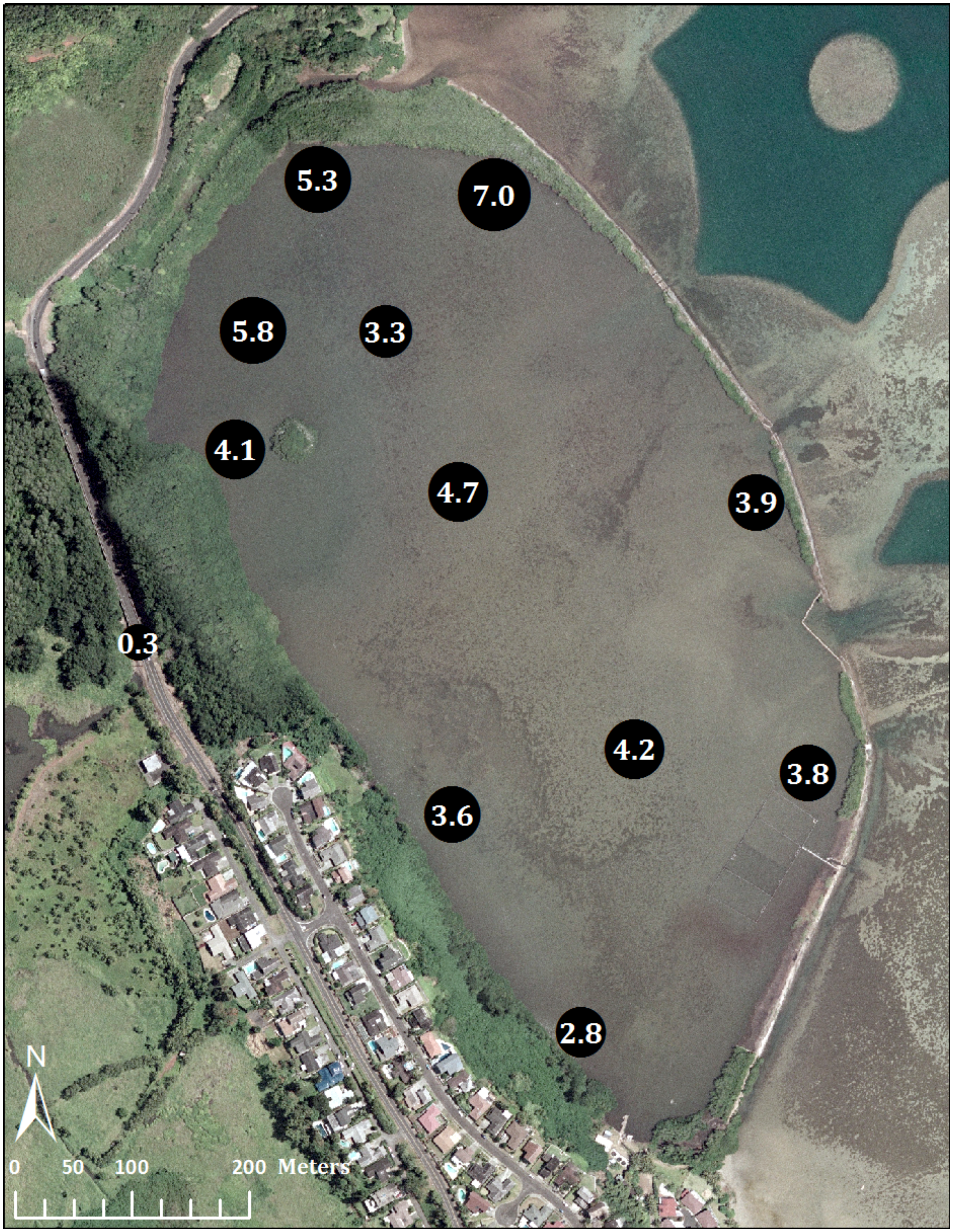


Figure 3.4 Radium-224:radium-223 activity ratios from full tidal cycle in Heʻeia Fishpond on 11/19/13

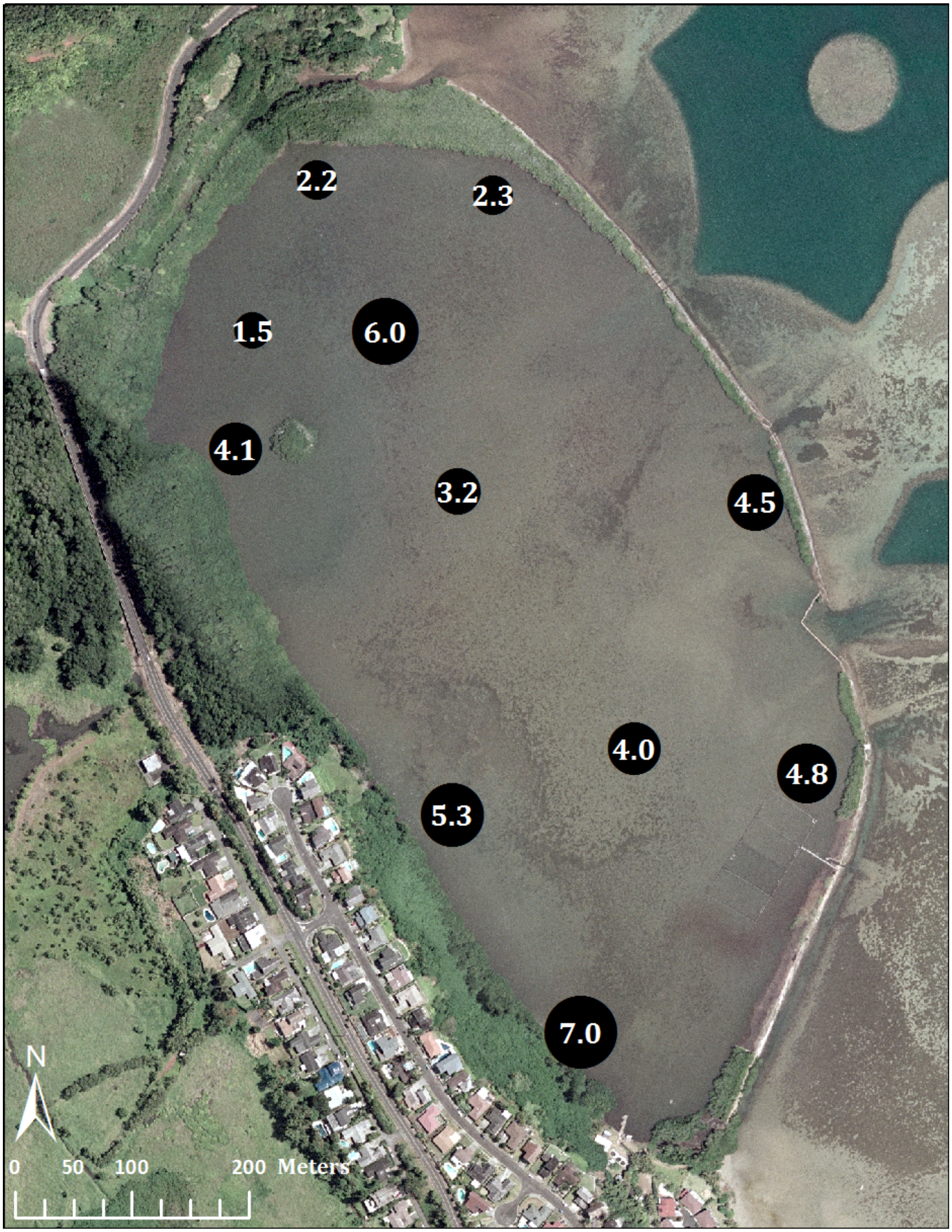


Figure 3.5 Water parcel residence times (days) in He'eia Fishpond on 11/19/13. Note stream value was inaccurate due to decay sample size one order of magnitude lower than values in the pond and thus was not reported.

Table 3.4 Submarine Groundwater Discharge in He‘eia Fishpond

Time (11/19/2013)	Latitude (N)	Longitude (W)	*Residence Time (days)	Track Distance (m)	Distance to Shoreline (m)	Average Depth (m)	Volume (m^3)	**Total Rn (dpm/m^3)	Inventory Rn (dpm)	SGD (m^3/day)	SGD (m^3/day per m shoreline)
13:15	21.43203	157.80703	7.03	97	18	0.33	576	5835	3359384	8.0	0.082
13:20	21.43353	157.80821	6.18	196	23	0.66	2970	14729	43752145	118	0.60
13:25	21.43467	157.80893	5.32	152	23	0.50	1749	9670	16913906	53.0	0.35
13:30	21.43595	157.80984	4.73	180	17	0.60	1841	2961	5449186	19.2	0.11
13:35	21.43741	157.81051	4.13	175	42	0.50	3680	13669	50310034	203	1.2
13:40	21.43885	157.81027	1.82	172	17	0.40	1167	5453	6363300	58.4	0.34
13:45	21.43898	157.80933	4.06	170	47	0.40	3203	3542	11346413	46.6	0.27
13:50	21.43751	157.80875	4.57	169	149	0.75	18938	5400	102258986	373	2.2
13:55	21.43608	157.80821	3.18	169	150	0.70	17794	5806	103318817	542	3.2
14:00	21.43466	157.80765	3.99	171	114	0.60	11717	12471	146123036	610	3.6
14:05	21.43336	157.80682	5.26	170	116	0.40	7906	8761	69259223	219	1.3
14:10	21.43356	157.80577	4.77	171	26	0.33	1470	8981	13199996	46.1	0.27
14:15	21.43505	157.80531	4.77	205	18	0.33	1215	16356	19869622	69.4	0.34
14:20	21.43708	157.80586	4.52	247	17	0.75	3148	8810	27733136	102	0.41
14:25	21.43882	157.80728	3.34	232	9	0.75	1568	6188	9701705	48.4	0.21
14:30	21.43949	157.80909	2.16	146	17	0.40	995	1152	1146490	8.8	0.060

*Estimated from apparent radium ages from Mn fibers left in He‘eia Fishpond over one tidal cycle

**Total Rn concentration corrected for losses by evasion & decay and inputs by diffusion & offshore Rn

Nutrients

Nutrients: Spatial Variability

Nutrient levels were assessed from nine samples taken at select locations across He‘eia Fishpond (see Table 3.5 on page 48). Total nitrogen ranged from 6.47-11.39 μmol/L (see Figure 3.6 on page 49). Small total N values were found in the center of the fishpond, while larger values were located along the terrestrial perimeter of the pond.

Nutrient Fluxes

Nutrient flux calculations indicate that both fresh and brackish SGD contribute substantial amounts of nutrients to He‘eia Fishpond. Fresh and brackish SGD bring in 32 and 140 mol/day DIN, respectively, greatly exceeding stream DIN flux of 11 mol/day (see Table 3.6 on page 50). In fact, brackish SGD nutrient fluxes outweigh fresh SGD and stream inputs in all nutrient categories that have complete data except $NO_3^- + NO_2^-$. He‘eia Stream seems to supply more DIP than does fresh SGD, and an equal amount of DOP compared to fresh SGD. From nutrient flux data, we deduce that brackish SGD likely brings in large quantities of recycled nutrients, while fresh SGD and the stream bring new nutrients into the pond.

Table 3.5 Nutrient Concentrations and Statistics in μmol/L in He‘eia Fishpond on 11/19/13

Sample ID	Latitude	Longitude	Total N	Total P	Phosphate	Silicate	N+N	Ammonia
HeeiaFP_N1	21.43475	157.80899	8.68	0.53	0.09	54.85	0.14	0.16
HeeiaFP_N2	21.43731	157.81049	11.39	0.66	0.24	228.55	0.01	0.20
HeeiaFP_N3	21.43942	157.80945	10.76	0.67	0.28	155.33	0.45	1.03
HeeiaFP_N4	21.43721	157.80844	6.47	0.61	0.05	24.87	0.30	0.25
HeeiaFP_N5	21.43451	157.80760	6.73	0.74	0.04	27.63	0.14	0.05
HeeiaFP_N6	21.43297	157.80606	6.92	0.95	0.05	19.67	0.13	0.31
HeeiaFP_N7	21.43470	157.80525	7.29	0.94	0.05	17.24	0.19	0.50
HeeiaFP_N8	21.43782	157.80643	8.25	1.01	0.09	25.46	0.54	1.04
HeeiaFP_N9	21.43935	157.80821	6.78	1.01	0.07	29.82	0.05	0.26
Minimum			6.47	0.53	0.04	17.24	0.01	0.05
Maximum			11.39	1.01	0.28	228.55	0.54	1.04
Average			8.14	0.79	0.11	64.82	0.22	0.42
Standard Deviation			1.82	0.19	0.09	75.13	0.18	0.37

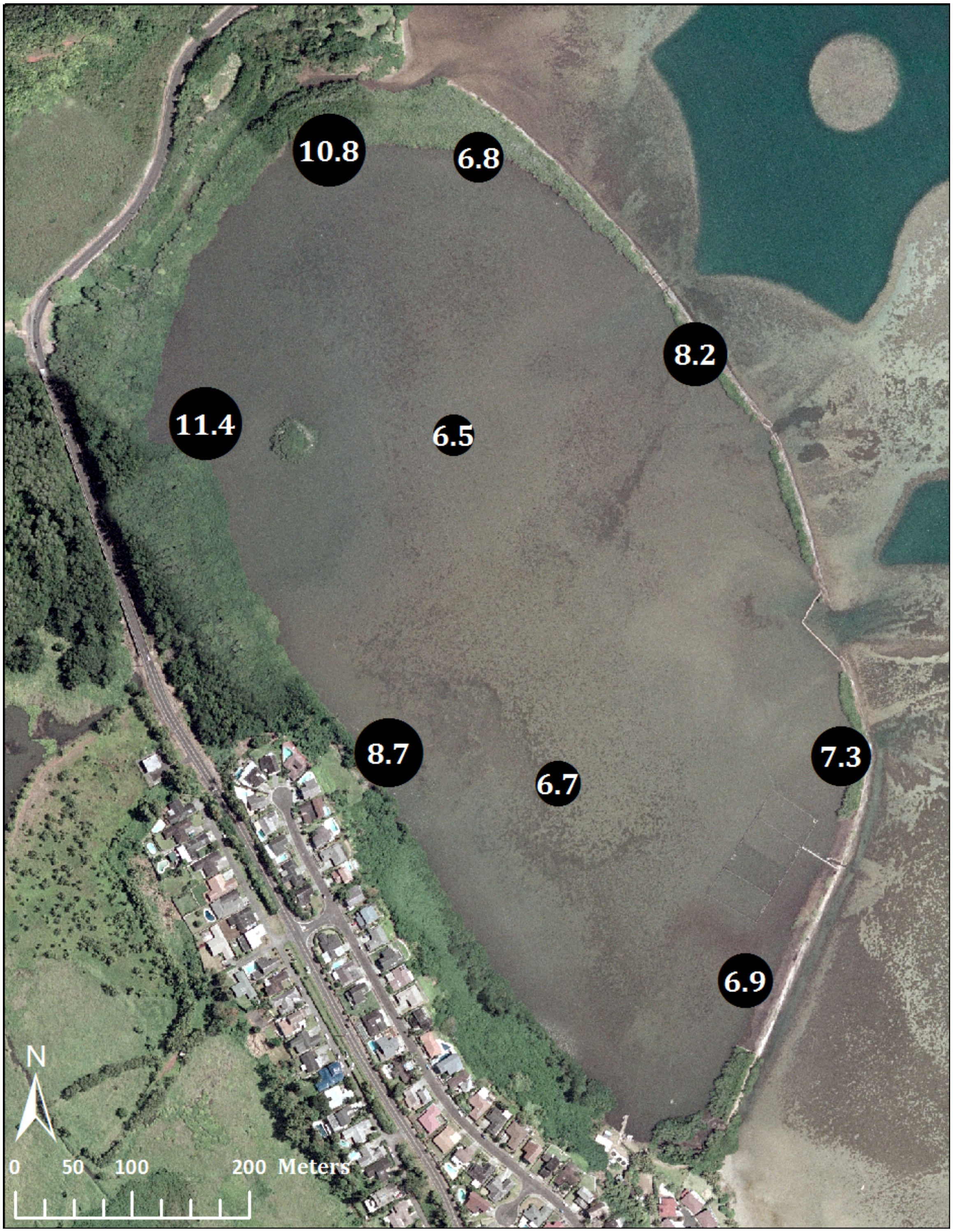


Figure 3.6 Total nitrogen (μmol/L) in He'eia Fishpond on 11/19/13

Table 3.6 Comparison of Nutrient Fluxes in He‘eia Fishpond in mol/day

	Total N	Total P	Phosphate	Silicate	N+N	Ammonia	DIN	DON	DIP	DOP
[1]**Fresh SGD**	37.12	0.65	0.18	53	4.1	28.3	32	4.8	0.18	0.47
[2]**Brackish SGD**	-	5.04	1.73	-	0.51	139.4	140	-	1.73	4.30
Total SGD	-	5.69	1.91	-	4.6	167.6	172	-	1.91	4.77
[3]**Stream**	23.53	1.97	1.50	840	10.3	0.7	11	12.5	1.50	0.47

[1]Original nutrient concentrations from Dulaiova 2013
[2]Original nutrient concentrations from Briggs et al. 2013
[3]Original nutrient concentrations from Hoover & Mackenzie 2009

DISCUSSION

<u>Groundwater Sources</u>

Salinity

He'eia fishpond is shallow (≤1m deep) and exhibits a vertical salinity gradient neighboring the area where He'eia Stream discharges into the pond. A freshwater lens floats on top of a saltier, brackish water mass. The gradient was distinctly visible in the field and confirmed by salinity measurements near the stream (surface: 11.5, bottom: ~30). Further east, where the seawall separates He'eia Fishpond from Kāne'ohe Bay, the water column is well-mixed, resulting in a relatively uniform vertical salinity profile (salinities of 32-33.5), particularly at the mākāhās.

In addition to a stratified water column, He'eia Fishpond contains distinct surface salinity regions influenced by tides, stream inputs, and groundwater discharge. With heavy inputs from He'eia Stream in the northwest corner of He'eia Fishpond where salinities were lowest, as well as surges from Kāne'ohe Bay on the eastern border, we see a defined salinity gradient ranging from 11.5-33.5.

Surface salinity in the pond is fairly stable over time except at the pond-sea interface where stream discharge dominates during low tide, as the pond and ocean fight for dominance at the mākāhās (see Figure 3.2 on page 39). Three CTD divers left over a full tidal cycle illustrate the uniformity of the pond's salinity in locations away from stream inputs and the seawall, and the highly variable and irregular salinity fluxes near the seawall. At stations 7 and 16, salinity remains fairly constant, decreasing by only 2-5 for ~4 hours around lower low tide. At station 3, vast fluctuations in salinity occur; changes by ~16 units repeat several times over one tidal cycle, loosely echoing water level but with much variability due to tidal action. This illustrates that the radium-collecting Mn fibers experienced variable conditions across the pond, but at peripheral stations, grab samples should represent radium activities close to tidally averaged values.

Radon & Salinity

Our goal in examining salinity and radon together was to determine SGD from meteoric waters versus recirculated pond or bay water. Meteoric SGD is driven by hydraulic gradients, while recirculated brackish SGD is driven by oceanic processes like tidal pumping and waves in addition to hydraulic gradients (Burnett et al. 2003). Hawaiian coasts tend to be highly permeable, as they are made up of basaltic rock and porous sedimentary deposits, allowing exchange between basal aquifer and coastal ocean to occur with ease (Street et al. 2008). As such, the aquifer, or subterranean estuary, that underlies He'eia Fishpond is connected to the surface and water is able to flow from one to the other relatively freely.

Exploring radon versus salinity trends, we can identify groundwater end-members to the fishpond (see Figure 4.1 on page 55). In region 1, where there is low salinity but high radon, the mixing line suggests surface water is influenced by fresh groundwater discharge. The radon value extrapolated to 0 salinity along these 4 data points is 4 dpm/L. This is lower than the observed groundwater radon values upstream of the fishpond, which were 60 dpm/L (Dulaiova, unpublished). The discrepancy could be for three reasons: 1.) due to radon evasion, radon activities in Heʻeia Fishpond do not reflect a conservative mixing line, 2.) due to different geological composition, groundwater near the fishpond sediments has lower radon equilibrium values than the upstream wetland, and 3.) active tidal pumping dilutes radon-rich groundwater resulting in lower radon activities in SGD.

Region 2 represents water that had elevated radon but high salinity, which may be a result of brackish groundwater discharge to the pond. Marine forces such as tidal pumping and large-scale seawater intrusion into the coastal aquifer may drive the brackish SGD. Values in region 3 have high salinity similar to that of Kāneʻohe Bay, but low radon only slightly elevated above baseline levels. Our radon vs. salinity distribution suggests that both fresh and brackish groundwater discharge are present in the pond.

Geographically, region 1 is located in the estuarine area where Heʻeia Stream discharges into the pond. Here, presence of fresh groundwater discharge is expected as the stream influences the hydraulic gradient, thus orienting groundwater flow lines into the streambed (Dulaiova et al. 2006). The highest saline radon activities were observed at the southwest side of the pond where, due to the shallow topography, recirculation of brackish groundwater through the intertidal zone is possible. Above-baseline radon activities were also observed near the seawall. Here, ocean tides may create a hydraulic gradient between the Heʻeia Fishpond and Kāneʻohe Bay, driving water through the underlying sediments. While this SGD is not of terrestrial origin, it may become enriched in nutrients as it flows through sediments loaded with organic matter.

The hydrologic setting in Heʻeia Fishpond can therefore be described using four main water pathways (see Figure 4.2 on page 55). Freshwater enters the pond from Heʻeia Stream and SGD, brackish water flows in via SGD, and seawater accesses the pond from Kāneʻohe Bay through the mākāhās. It is interesting to note that the highest fresh and highest brackish radon values are similar, indicating that there is very slow recirculation in the pond resulting in groundwater residence times long enough to allow the radon to reach equilibrium. This is not surprising, as there is basically no wave action within Heʻeia Fishpond.

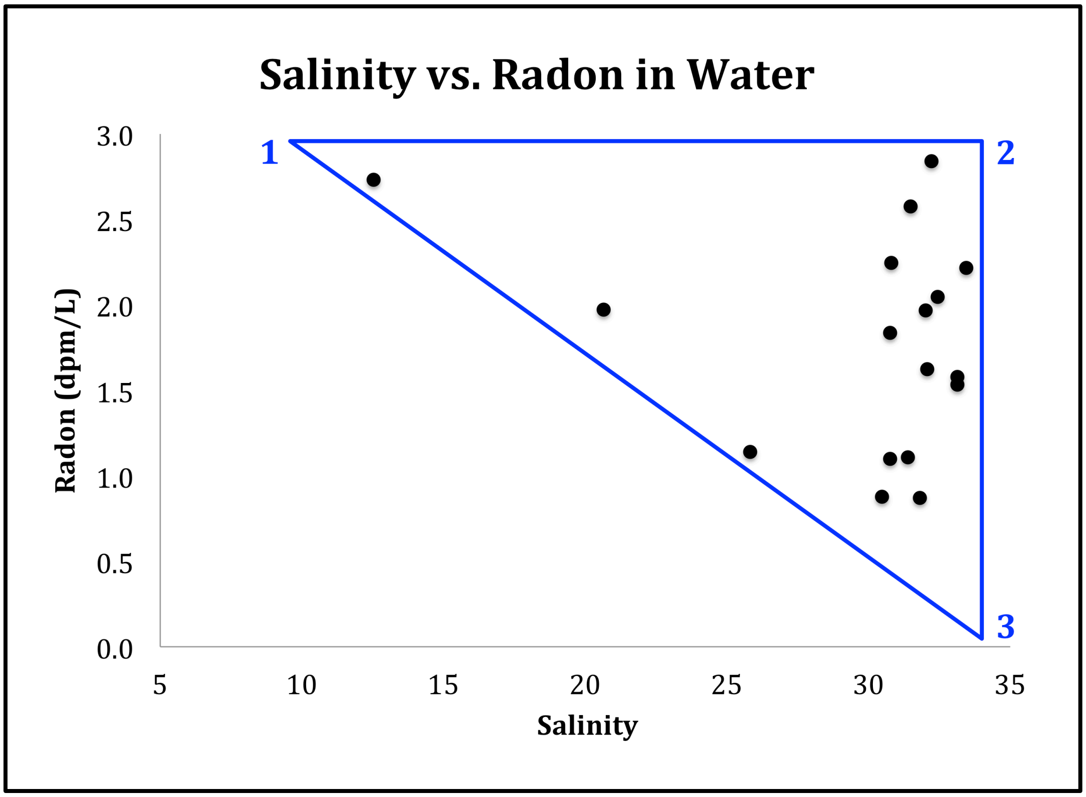


Figure 4.1 Salinity vs. radon in water in He'eia Fishpond on 11/19/13

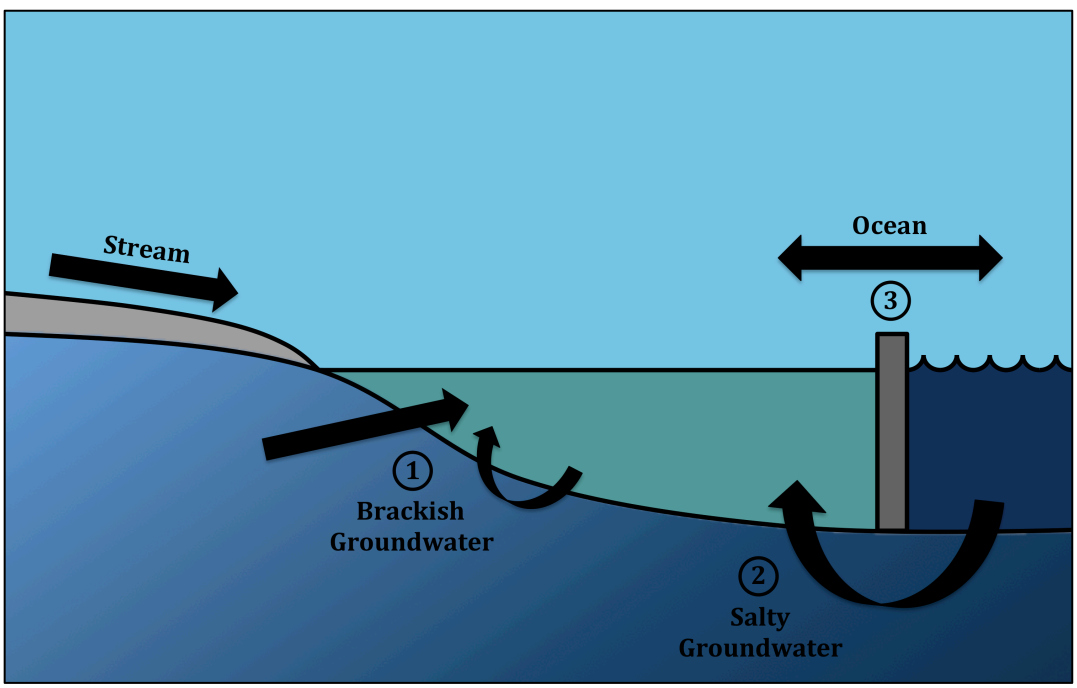


Figure 4.2 Conceptual model of water fluxes in He'eia Fishpond

Submarine Groundwater Discharge

Radium: Water Residence Time

Radium isotope activities from this study are comparable to those from other research conducted in the Hawaiian Islands. Knee et al. 2008 reports near-shore ^{224}Ra activities ranging from 21-35 dpm/m^3 in Hanalei Bay, Kauaʻi, and 6-10 dpm/m^3 in Haʻena State Park, Kauaʻi. Radium-224 activities in Heʻeia Fishpond from our grab samples range from 13-39 dpm/m^3.

Knee et al. 2008 also reports estimated maximum residence time for near-shore water in both study sites as 64.6 hours, or ~2.7 days. Residence times calculated from ^{224}Ra:^{223}Ra in Heʻeia Fishpond ranged from 1.8-7.0 days. The long residence times revealed during our ^{224}Ra:^{223}Ra calculations point to restricted flushing of several regions of the pond, resulting in long radon residence times; this caused significant diffusion, evasion, and decay corrections in Equation 4.

SGD in Heʻeia Fishpond

High ^{222}Rn values, which we used as a proxy for SGD, adequately corresponded to locations we calculated to have high SGD flux. Where Heʻeia Stream discharges, ^{222}Rn values of 2.7 and 2.0 dpm/L indicated groundwater presence (see Figure 3.1 on page 35). Parallel SGD measurements were 1.1 and 0.34 m^3/day per meter of shoreline. High ^{222}Rn values on the south-west shoreline were also witnessed with activities of 2.6, 1.8, and 2.8 dpm/L, matching up with SGD of 0.60, 0.35, and 3.6 m^3/day/m shoreline. Along the seawall, where we saw ^{222}Rn values of 2.1, 2.3, and 2.2, SGD was 0.34, 0.41, and 0.21 m^3/day/m shoreline. To calculate SGD we did not map the full extent of individual groundwater plumes, but instead used plume width as distance to nearest shoreline to calculate volume of the pond each radon track represented. For this reason, since we were very close to the seawall while conducting our survey (<20m), groundwater plumes may have reached further into the pond, possibly resulting in SGD values lower than true.

SGD vs. He‘eia Stream Water Inputs

Streams and rivers tend to get the most credit for transport of freshwater to the coastal ocean, however our results indicate significant contributions of both fresh and brackish groundwater to He‘eia Fishpond. Table 4.1 and Figure 4.3 on page 58 compare fresh and brackish SGD to He‘eia Stream water input. Although this is not a complete water budget, as ocean input is not represented, influx of water from SGD compared to the stream is about one-to-one. Stream input was 2139 m^3/day, which was slightly below the 10-year He‘eia Stream discharge average. Our SGD:stream ratio is significant, meaning SGD must be considered in the hydrology of He‘eia Fishpond and explored further during above- and below-average stream discharge conditions.

Table 4.1 Water Flux from SGD and Stream Inputs to He‘eia Fishpond

	Water Influx (m^3/day)	Source
Fresh SGD	317	
Brackish SGD	2209	This study
Total SGD	2525	
He‘eia Stream Discharge 11/18-20/13	2139	USGS

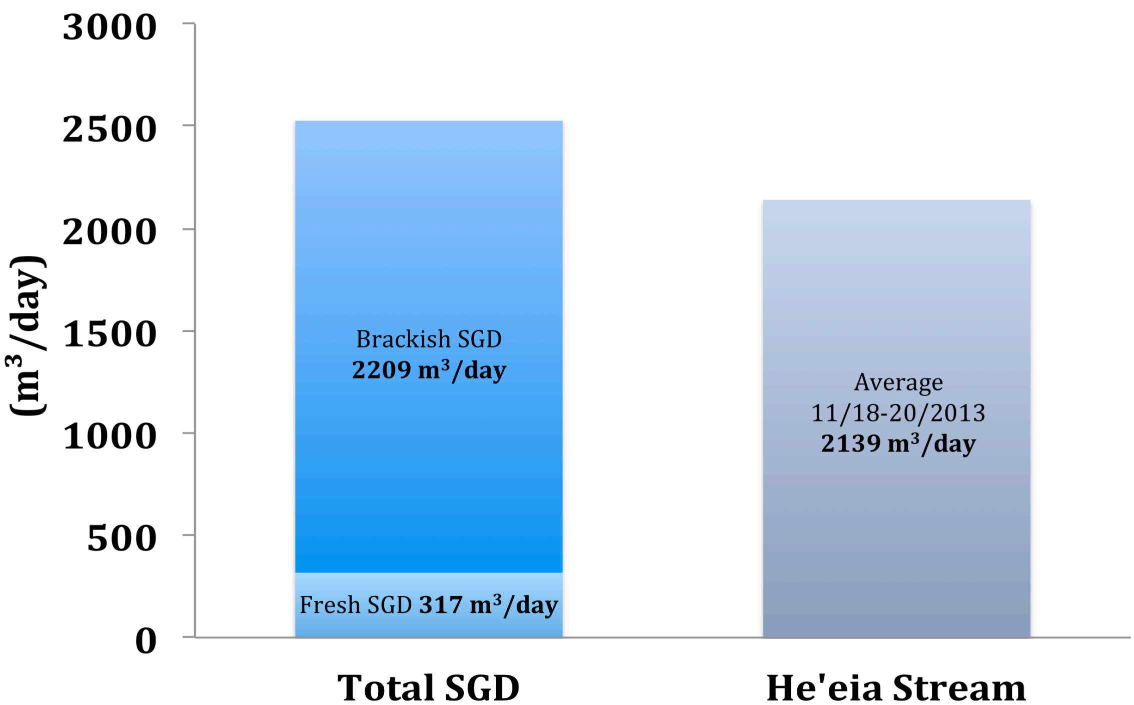


Figure 4.3 Comparison of SGD and stream inputs to He‘eia Fishpond

Nutrients

Submarine groundwater discharge is not only volumetrically important, but chemically as well. Nutrients enter coastal zone via rivers, atmosphere, upwelling, and SGD (Burnett et al. 2003). Since nutrient concentrations in groundwater are usually high in comparison to seawater, discharge of groundwater to coastal areas can be of great importance to coastal ecosystem nutrient budgets (Street et al. 2008). Nutrients in groundwater can have significant effects on water quality as well, and can greatly contribute to eutrophication in coastal zone (Burnett et al. 2003).

Nutrient Concentrations

Dissolved silica (DSi) is present in very high concentrations in Hawaiian groundwater as an effect of young basaltic rock weathering. For this reason, DSi has been successfully used as a proxy for SGD in Hawaii as well as other locations (Street et al. 2008). In He‘eia Fishpond DSi was measured at 65 μmol/L (this study) and 54 μmol/L (Young 2011, see Table 4.2 on page 63). It was estimated that 53 mol/day DSi are brought into the pond from fresh SGD, 840 mol/day DSi enter the pond via He‘eia Stream, and an unknown amount of DSi passes in from brackish SGD. We can see from our results that He‘eia Stream is unusually high in DSi at 392 μmol/L (Hoover & Mackenzie 2009), particularly compared to He‘eia Wetland groundwater DSi measured at 167 μmol/L (Dulaiova 2013). It could therefore be inferred that DSi would not be a reliable proxy for SGD in He‘eia Fishpond as the groundwater signature is overwhelmed by stream inputs.

High ammonium in He‘eia Wetland (see Figure 4.4 on page 64) can be attributed to the vast spread of California grass and resultant buried organic matter. The grass contributes large amounts of organic material to water in the wetland, resulting in high microbial activity, anoxic conditions, and a subsequent increase in ammonium. The very high ammonium concentration in He‘eia Wetland groundwater (89 μmol/L) could potentially contribute to the high nitrate levels observed in the pond due to ammonium in groundwater becoming oxidized as it passes through the aquifer, reaching the pond interface and discharging as NO_3^- in groundwater discharge.

DIP, or phosphate, is unusually sparse in the waters of He‘eia Ahupua‘a. He‘eia Wetland groundwater, He‘eia Stream, and He‘eia Fishpond concentrations of phosphate are all low (<1 μmol/L). As seen in Figure 4.4 on page 64, even highland groundwater phosphate concentration does not exceed 2 μmol/L. This is in contrast to other observations in Hawaii (e.g. Johnson et al. 2008) and is a result of high amounts of iron (oxy)hydroxides in the stream and aquifer, which sorb phosphate and remove it from the soluble fraction (Dulaiova 2013).

Nutrient Fluxes

He‘eia Fishpond receives nutrients from both freshwater and saltwater sources. In most Hawaiian Fishponds, it is typical for the majority of new nutrients to come from stream input. However, there are indications that a significant amount of nutrients is entering Heʻeia Fishpond via fresh and brackish groundwater.

Ocean and rain nutrient fluxes were not assessed during this study. Ocean water enters Heʻeia Fishpond through the mākāhās irregularly, as seen at Site 3 (see Figure 3.2 on page 39), though the trend loosely follows water level indicating that flow is somewhat affected by tide. From Table 4.2 on page 63, we see that nutrient concentrations in Kāneʻohe Bay are less than Heʻeia Pond, Heʻeia Stream, and Heʻeia Wetland groundwater nutrient concentrations in all categories except total N. Therefore, it can be supposed that the amount of nutrients arriving in the pond via the ocean is small in comparison to the stream and SGD. Atmospherically-derived freshwater is assumed to provide a negligible amount of nutrients to .15-square-mile Heʻeia Fishpond compared to the stream and SGD. The amount of water and particulate matter discharged into the pond via the stream, nonetheless, is heavily influenced by amount of rainfall in Heʻeia Watershed as well as storm events.

Coastal productivity is often limited by nitrogen (McGowan 2004). Concentrating on dissolved inorganic nitrogen fluxes, we see that both fresh and brackish SGD inputs of DIN to Heʻeia Fishpond outweigh stream inputs of DIN (see Figure 4.5 on page 65). Nutrients entering the pond via brackish SGD are not necessarily new nutrients, however. The nutrients may be recycled within the pond, whereas fresh SGD and the stream bring in new, terrestrially-derived nutrients.

Compared to the stream, brackish SGD brings in more total P, DIP, and DIN (see Figure 4.5 on page 65), but again much of it is recycled. This does not mean that recycling of nutrients lacks importance, as nutrients are still being made available to organisms in the pond. In terms of new nutrients, the stream brings in more total P and phosphate than does fresh SGD.

As mentioned earlier, our results are based on baseline stream discharge. During extreme events such as storms, stream discharge increases dramatically, resulting in considerable nutrient flux changes. Future SGD research should encompass non-baseline streamflow in comparisons.

Enrichment of nutrients in coastal waters due to human activities has been studied in depth in terms of runoff-caused eutrophication. Eutrophication can be overwhelmingly damaging to coastal ecosystems. It would be interesting to explore how land use enriches groundwater in nutrients, and if SGD could be a cause of ecologically damaging eutrophication as a result.

Table 4.2 Comparison of Average Nutrient Concentrations in He‘eia Ahupua‘a and Kāne‘ohe Bay in µmol/L

	Total N	**Total P**	**Phosphate**	**Silicate**	**N+N**	**Ammonium**	**Source**
He‘eia Fishpond	8.14	0.79	0.11	65	0.22	0.42	This study
	-	-	0.32	54	0.19	3.22	Young 2011
Southern Kāne‘ohe Bay	8.28	0.26	0.11	7	0.14	0.17	Ringuet & Mackenzie 2005
[1]He‘eia Stream	11.00	0.92	0.70	392	4.80	0.34	Hoover & Mackenzie 2009
He‘eia Wetland Groundwater	117.13	2.06	0.57	167	12.89	89.19	Dulaiova 2013
He‘eia Fishpond Pore Water	-	1.35-3.23	0.11-1.3	-	0.16-0.33	50.54-69.44	Briggs et al. 2013

[1]Hoover and Mackenzie (2009) report median nutrient concentrations

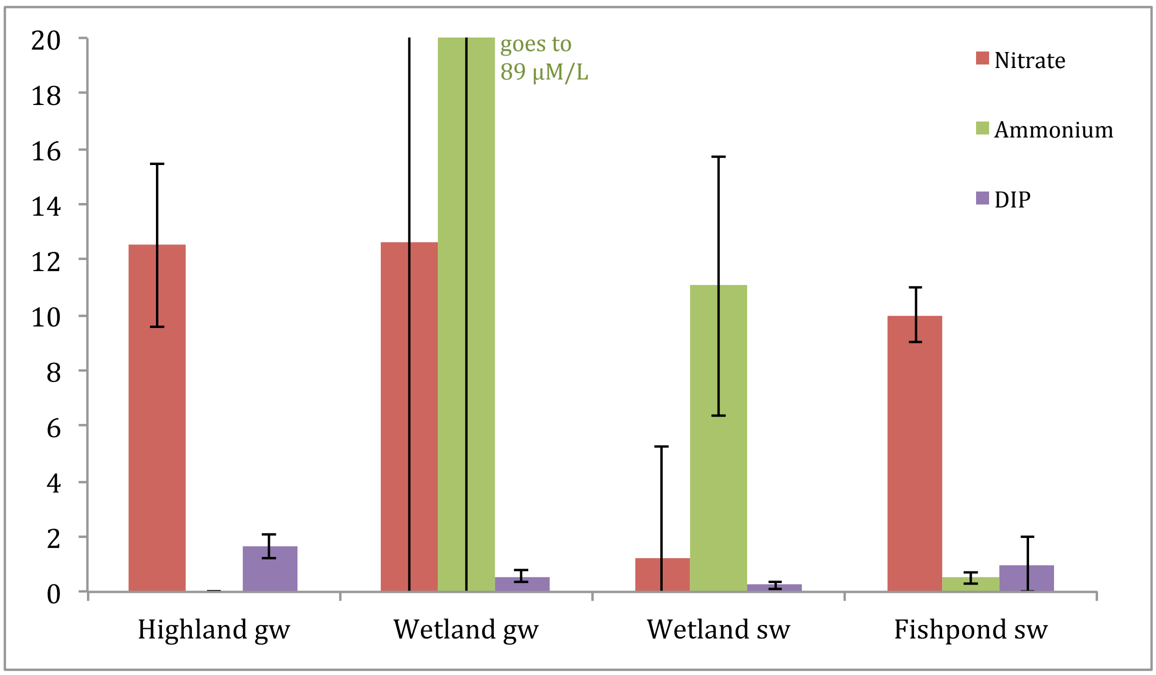


Figure 4.4 Nutrient concentrations (µmol/L) in He‘eia Ahupua‘a

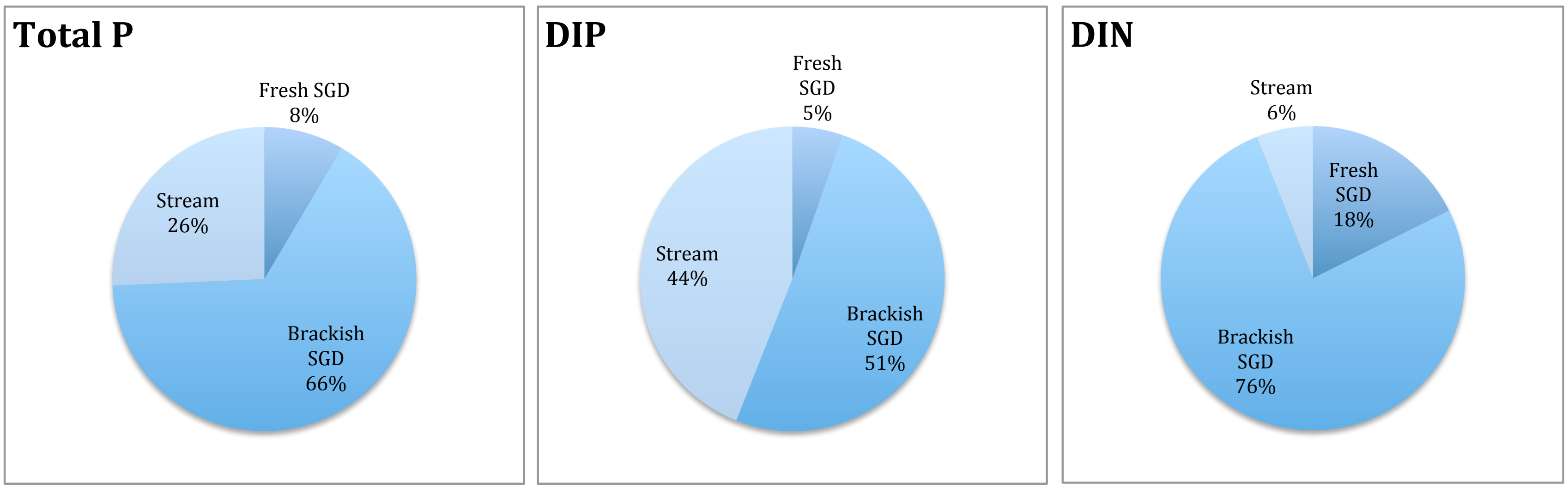


Figure 4.5 Comparison of nutrient fluxes from SGD and stream inputs to He‘eia Fishpond

CONCLUSIONS

Climate change and over-population have led to recent decreases in groundwater storage and recharge, as well as groundwater quality concerns. Implications are pervasive, especially in the State of Hawaiʻi, where the majority of domestic drinking water comes from groundwater. Threats to ocean health are also imminent. The ocean is a vital resource in Hawaiʻi, providing residents and visitors alike with economic and recreational benefits, and as such should be valued, studied, and protected.

Traditional hydrology has been principally concerned with terrestrial freshwater in lakes, rivers, and streams. Nevertheless, research has lately looked towards examination of the *other* source of terrestrial water to the oceans: submarine groundwater discharge. In recent years, scientists have recognized the importance of groundwater flow to coastal zones. SGD must be taken into consideration in order to gain a comprehensive view of geochemical fluxes to coastal areas.

Both fresh and brackish SGD are present in Heʻeia Fishpond, discharging at a cumulative rate of over 2500 m^3/day. Comparing SGD to Heʻeia Stream discharge, the ratio is about one-to-one. The stream is not the only significant pathway for water to the pond. Groundwater flow is also an important conduit for biologically important materials to the ocean. In particular, SGD can bring new nutrients to coastal zones.

He‘eia Fishpond, located in Kāne‘ohe Bay on O‘ahu, Hawai‘i, is a prime example of a coastal ecosystem that receives significant amounts of nutrients from SGD. Fresh SGD introduces a comparable amount of new nutrients in comparison to He’eia Stream. Brackish SGD nutrient fluxes are so high that we suspect the recycling of nutrients via brackish groundwater flow. Water and coastal resource management in Hawai‘i should further encompass groundwater and submarine groundwater discharge. Although streams and rivers may provide the most nutrients, sediments, and freshwater to coastal areas worldwide, SGD is not a pathway to be neglected.

Returning to the He‘eia Fishpond ecosystem diagram (Figure 1.8 on page 23), this project has provided a better understanding of the flow of nutrients into He‘eia Fishpond. Results suggest that there is nutrient cycling through trophic levels occurring via brackish SGD. These findings open new questions for research. SGD cannot be overlooked as a prominent source of nutrients to He‘eia Fishpond. The contribution of nutrients to coastal ecosystems from submarine groundwater discharge merits more attention.

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